PTOLEMY
Detecting Relic Neutrinos

Andi Tan
Princeton University

Snowmass Community Summer Study
21st July 2022

Cosmic Neutrino Background

Frozen-out at ~ 1 s

Temperature

$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \sim 1.95\ \mathrm{K\ or}\ 0.168\ \mathrm{meV}$$

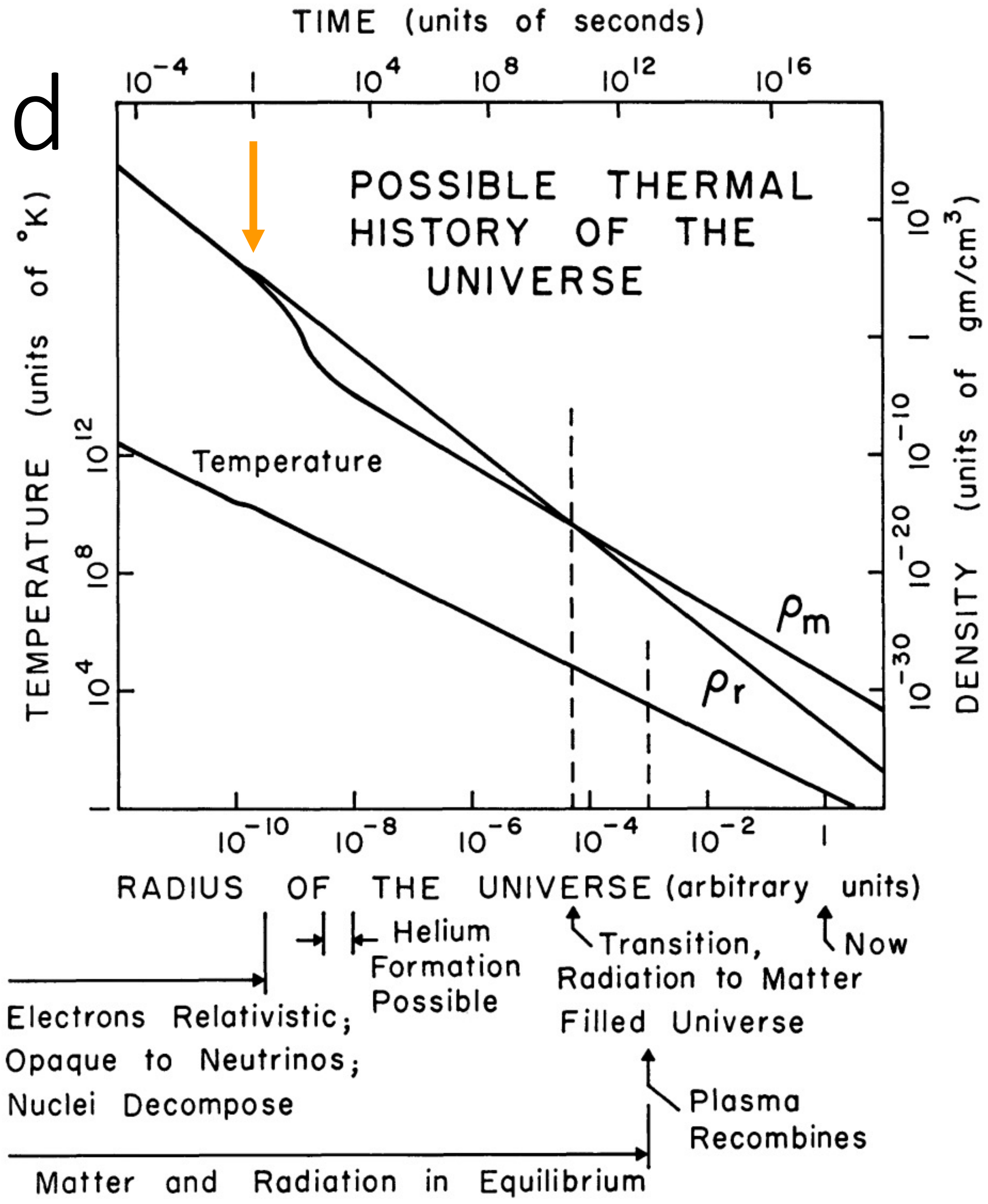
Number Density

$$n_\nu \sim 112\ /\mathrm{cm}^3 \text{ per flavor}$$

Momentum/Velocity Distribution

$$\langle v \rangle \sim 4.106 \frac{T_\nu}{m_\nu}$$

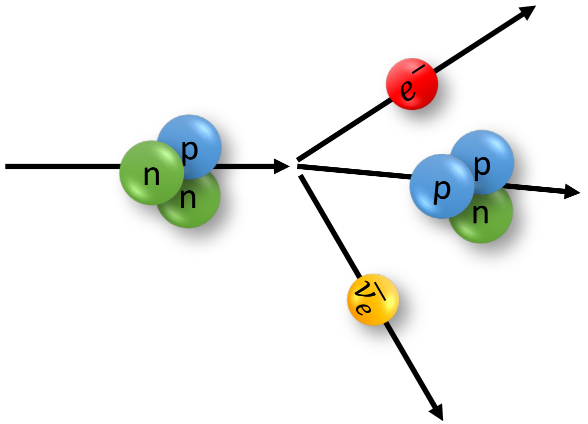
For $m_\nu = 50$ meV, $\langle v \rangle / \mathrm{c} \sim 0.014$



Dicke, Peebles, Roll, and Wilkinson, 1965, "Cosmic Black-Body Radiation.," Astrophysical J **142**, 414.

Detecting CνB via Neutrino Capture

Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in **1962** applied for the first time to massive neutrinos in **2007** by Cocco, Mangano, Messina



Gap (2m) constrained to

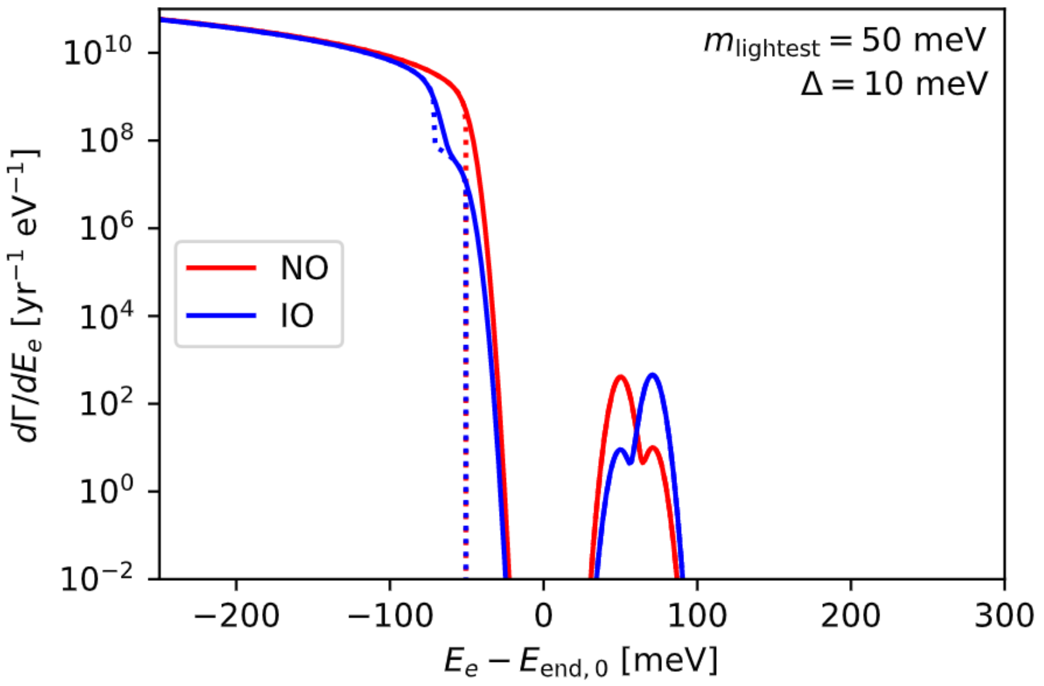
m < ~200meV

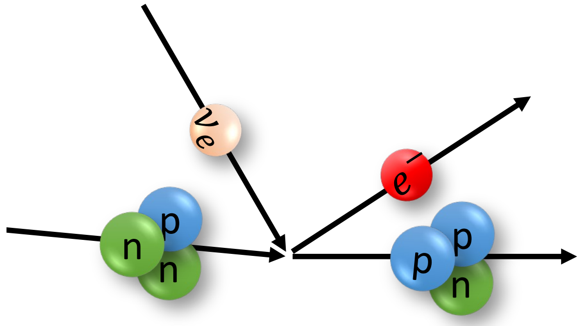
from **precision cosmology**

Electron flavor expected with

m > ~50meV

from **neutrino oscillations**





PTOLEMY:

$10^{-4} \times 10^{-2}$

compact filter + microcalorimeter

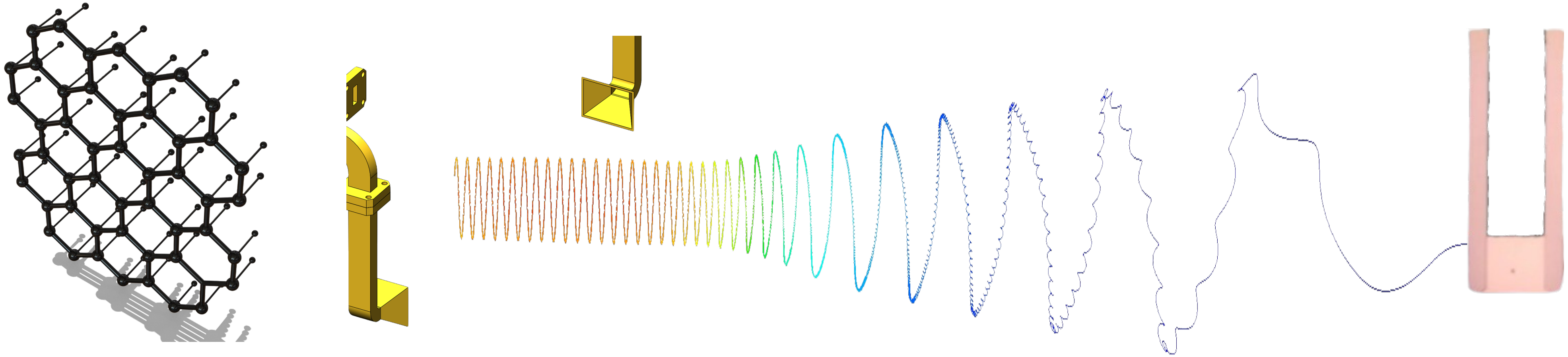
<u>**CνB Detection Requires:**</u> energy resolution $\mathcal{O}(10^{-6})$

KATRIN current upper limitation 0.8 eV/c^2 *Nature Physics* **18**,160–166 (2022)

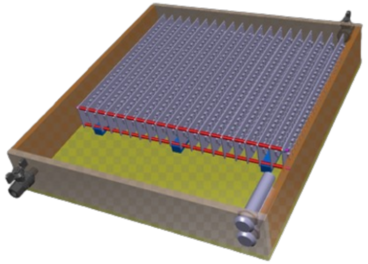
→ 0.2 eV/c^2 Sensitivity Goal with ~1 eV energy resolution (~10^{-4})

* Weinberg,. *Phys Rev* **128**, 1457–1473 (1962). **Cocco, Mangano & Messina, *J Phys Conf Ser* **110**, 082014 (2008).

Target: Relic Neutrino Capture → **RF Tracker:** Electron Pre-Measurement → **Dynamic Filter:** Selects endpoint electron in narrow 10^{-4} energy window → **Micro-calorimeter:** Measures $\mathcal{O}(\mathrm{eV})$ electron to 10^{-2} energy resolution



HV
18.6kV



$$E_{Total} = q\left(V_{TES} - V_{Target}\right) + E_{RFcorr} + E_{cal}$$

Recent Developments on PTOLEMY

- Prototype filter magnet completed and tested
- New TES performance – reaching 50 meV resolution for 15x15 μm^2 @ 52mK pixels
- New RF calculations and antenna simulations w/ Dutch collaboration on front-end processing
- End-to-end simulations in Kassiopeia for prototype
- >90% hydrogen loading on NPG graphene and theoretical developments on target physics
- Plans for LNGS full-prototype (funded by JTF)

Electromagnetic Filters

Transverse Drift filter

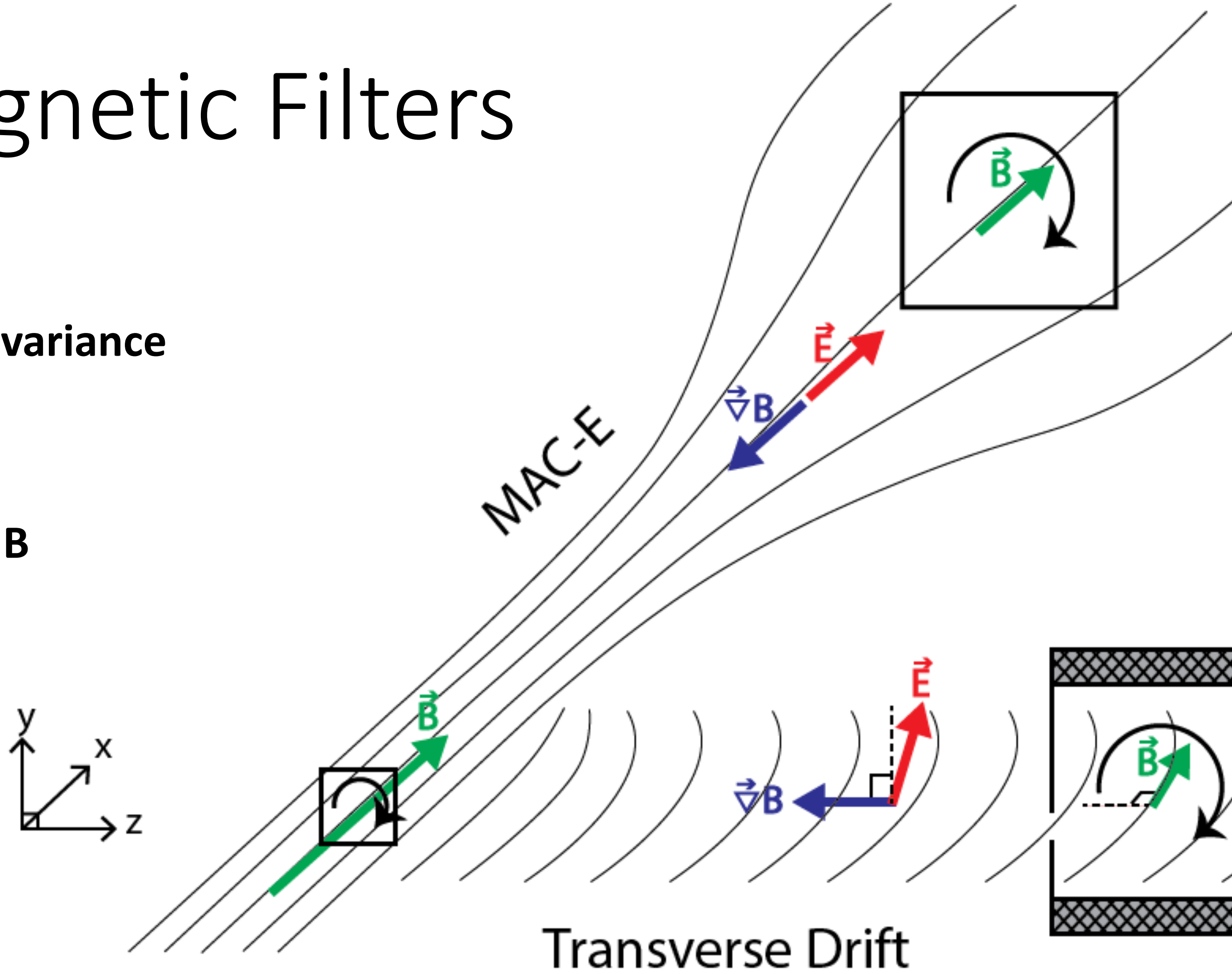
Magnetic Adiabatic Invariance

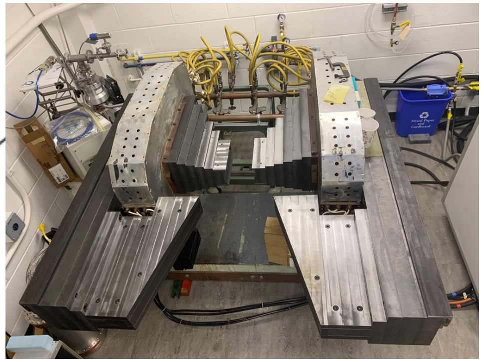
$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

No Collimation: -∇B⊥B

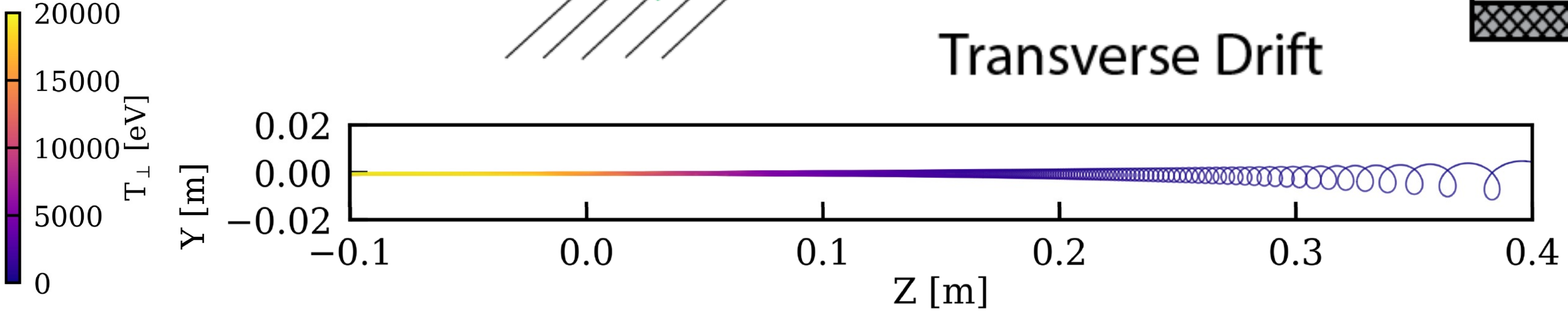
Filter (E - Field)

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B \times \boldsymbol{B})$$

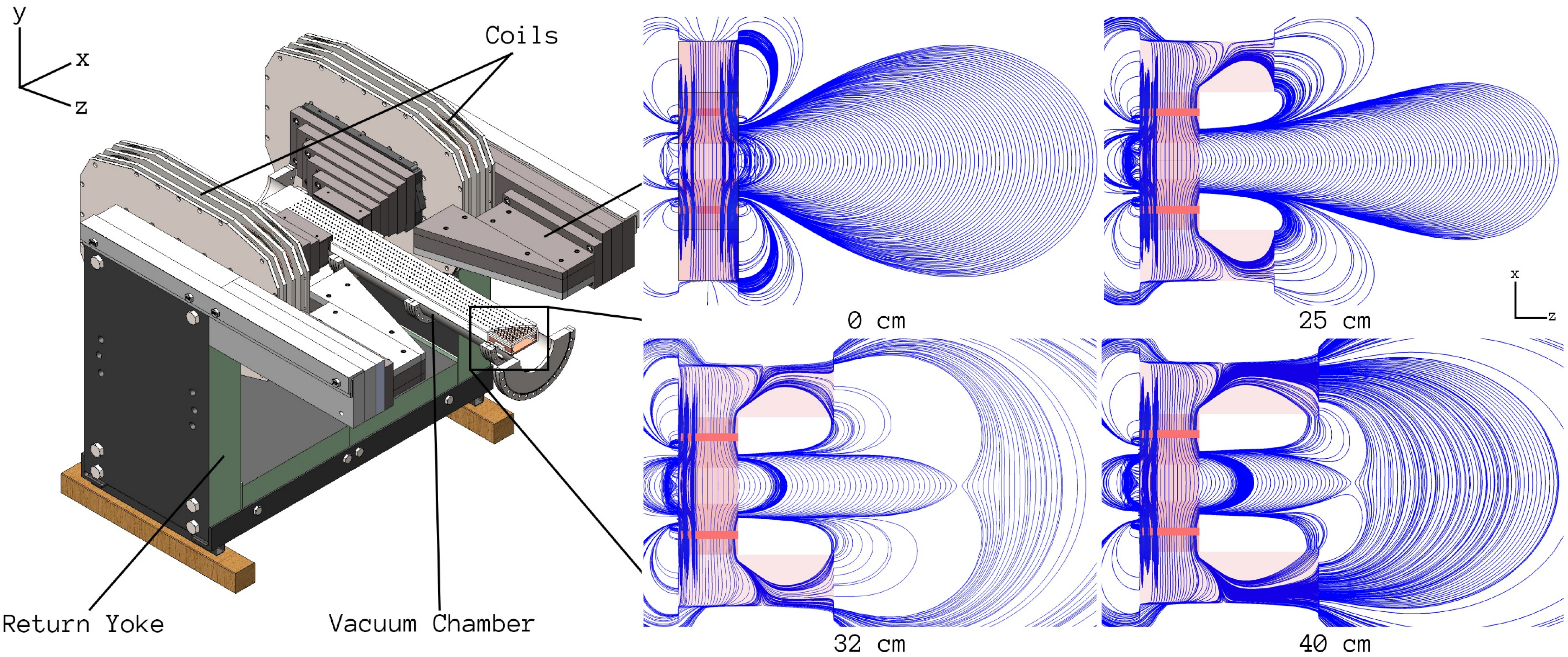




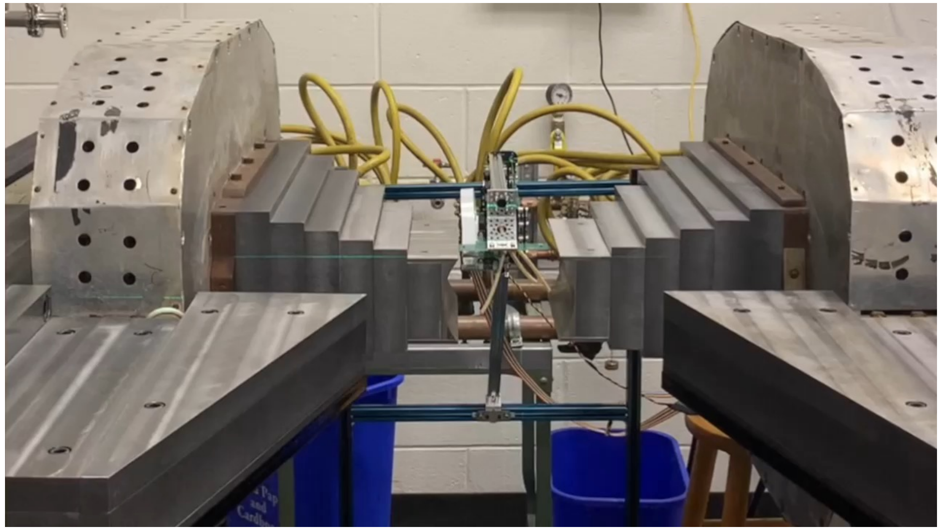
PTOLEMY ~1m³

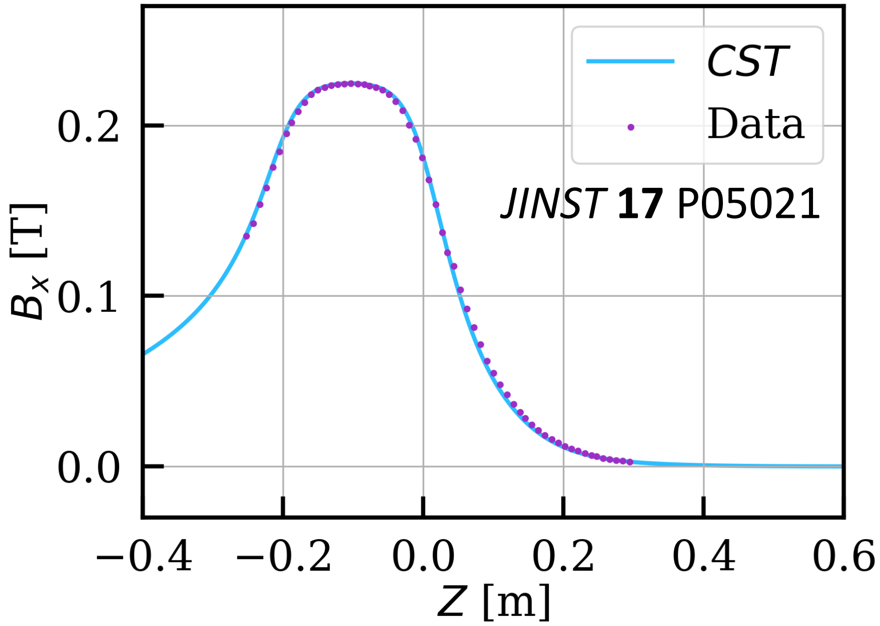


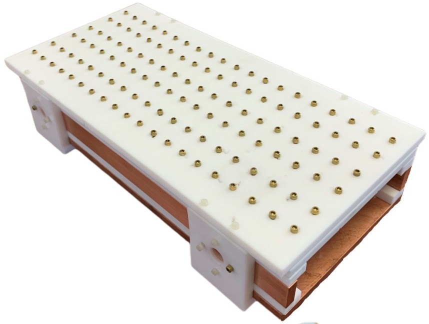
Princeton Magnet design

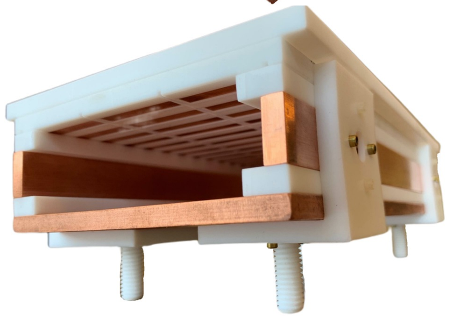


Commissioning of the Princeton Magnet







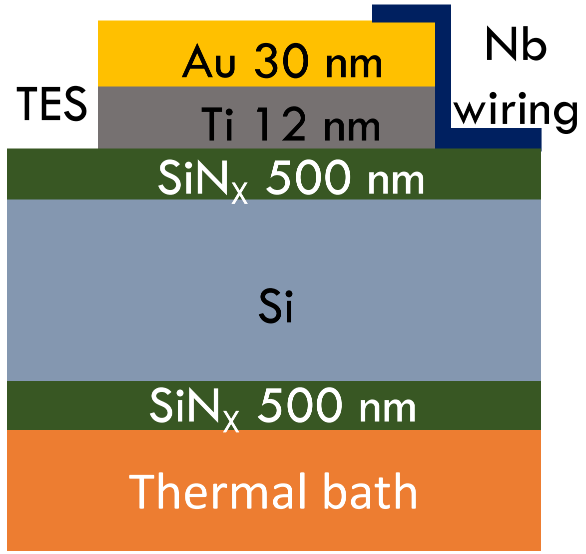


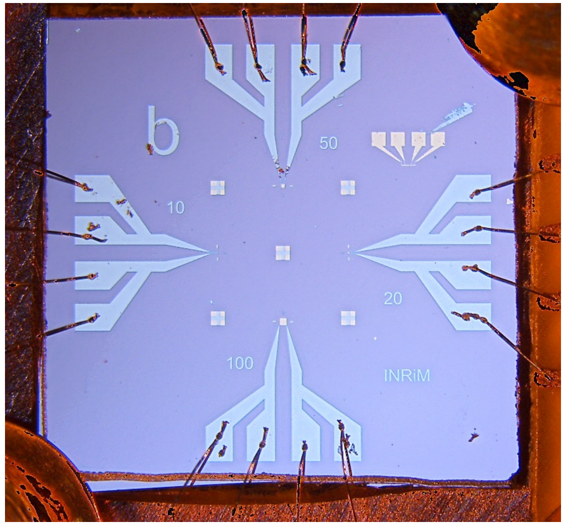
The B_x field was mapped out by digital 3-axis hall magnetic sensors.
Initial test at low power found good agreement between the measured and simulated fields.
A shorter version of filter was built for investigation.
Vacuum system is under design

Filter performance Improves as B^2 for a fixed filter dimension

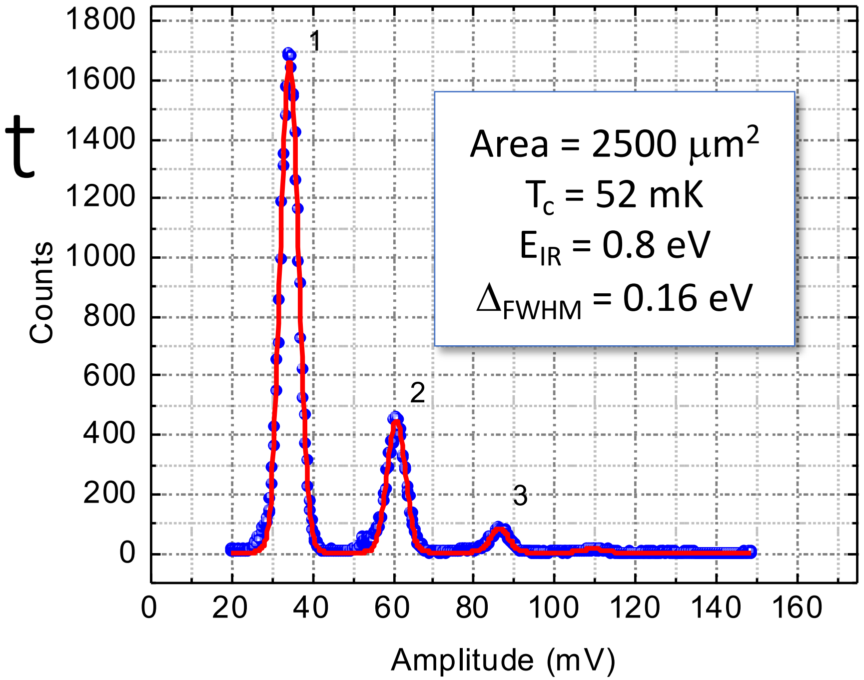
18.6 keV @ 1T → ~10eV (in 0.4m)
18.6 keV @ 3T → ~1eV (in 0.6m)

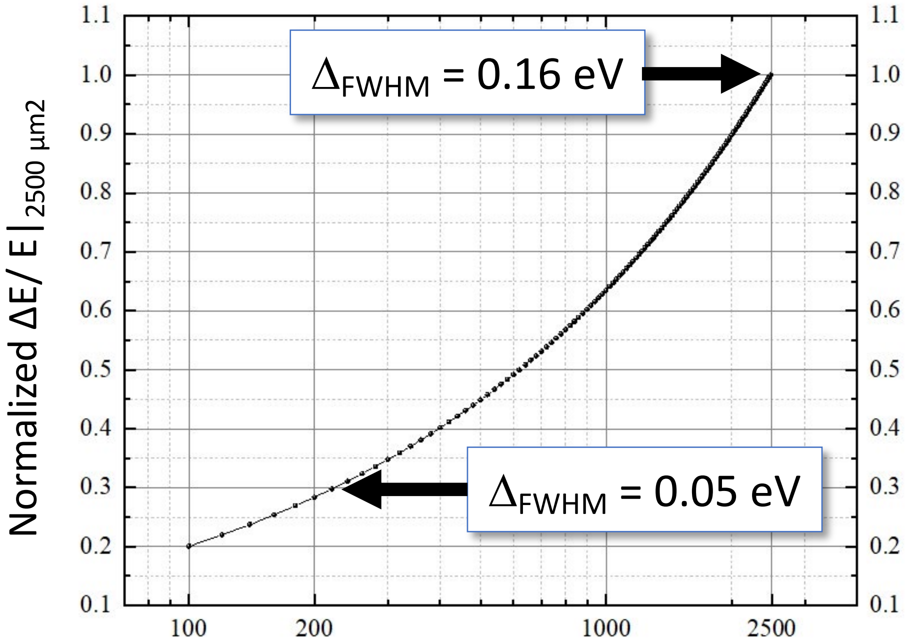
Transition Edge Sensor Development





TES Layout





TES evaluated initially by IR photons in ADR setup at INRiM

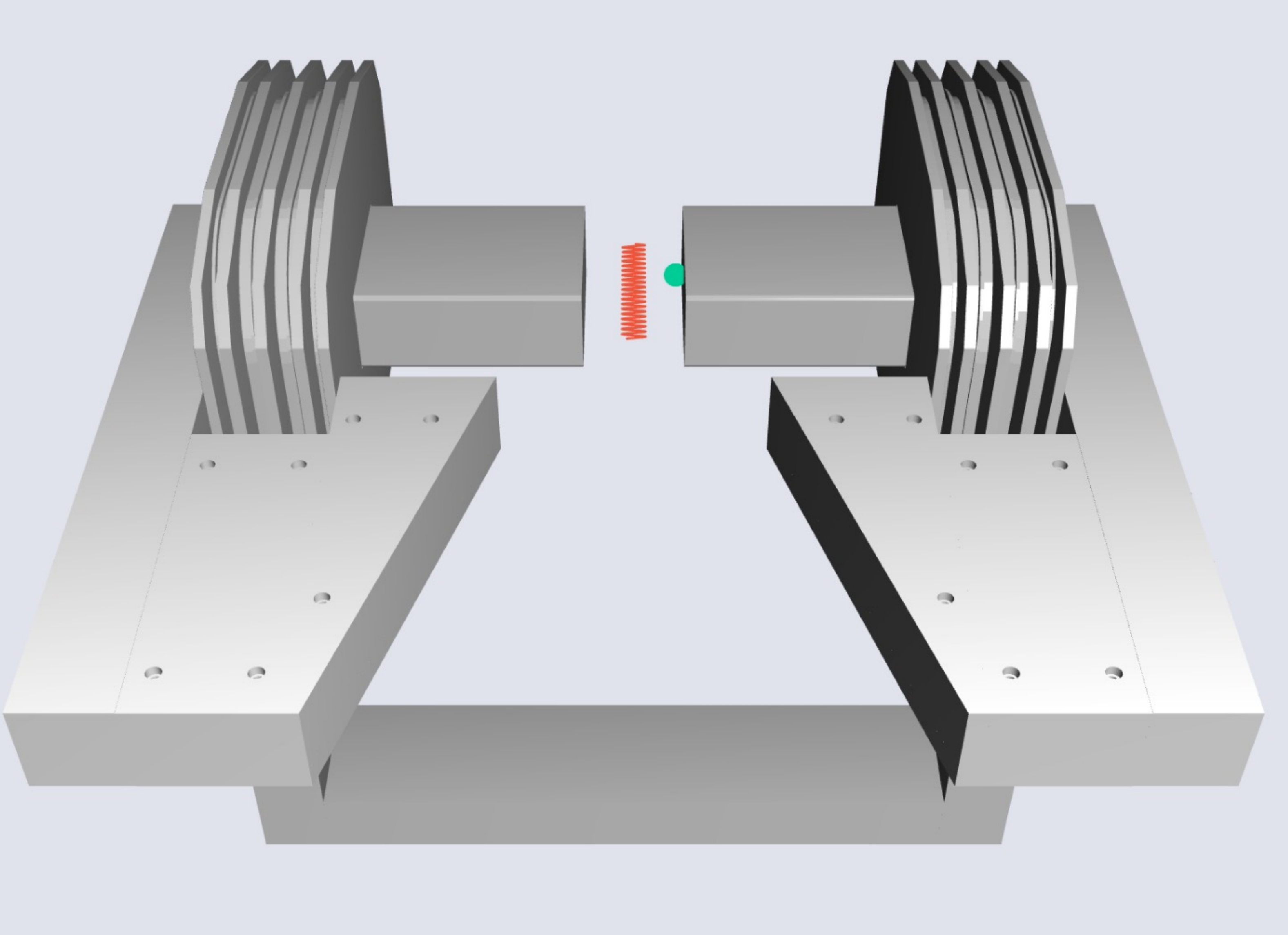
Optimize the thickness of Ti/Au to tune energy resolution $\Delta E \propto T_c^{3/2} t^{1/2}$, where t is Ti Thickness.

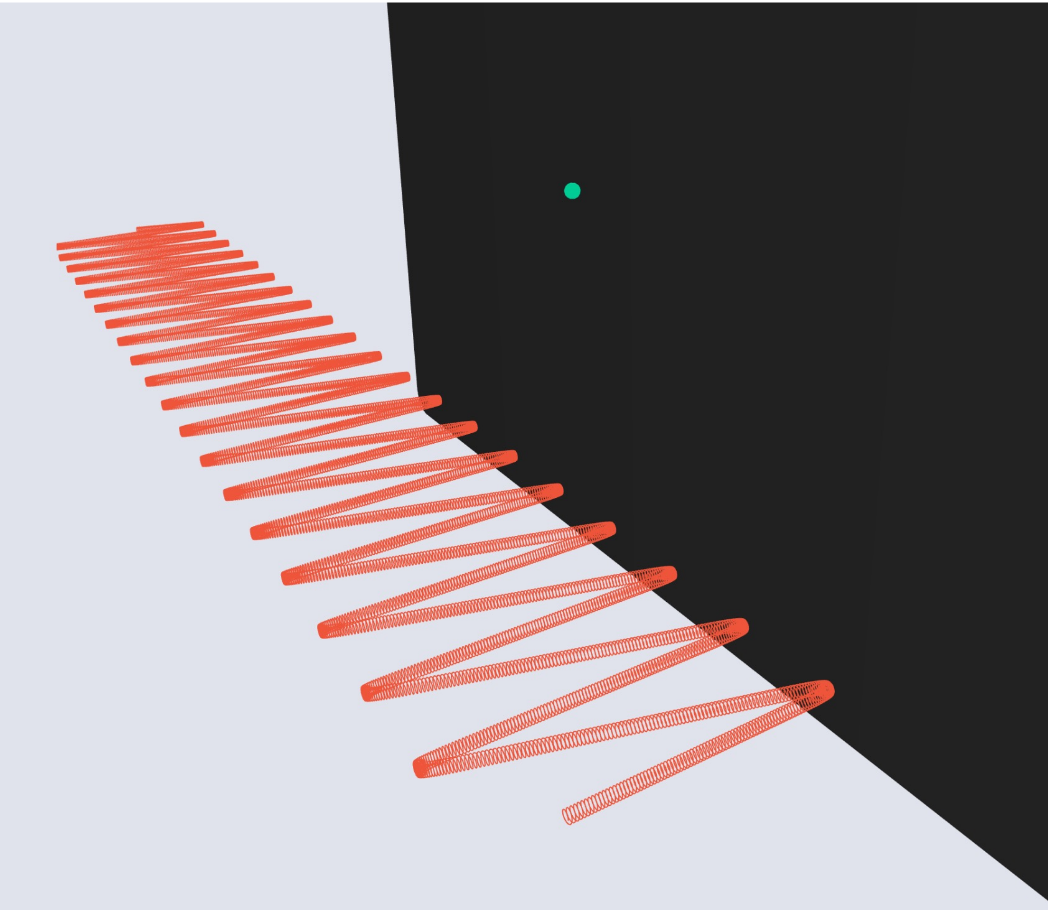
Resolution of ~ m$_\nu$: Area ~ 15 μm x 15 μm → Demonstrate with electrons

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

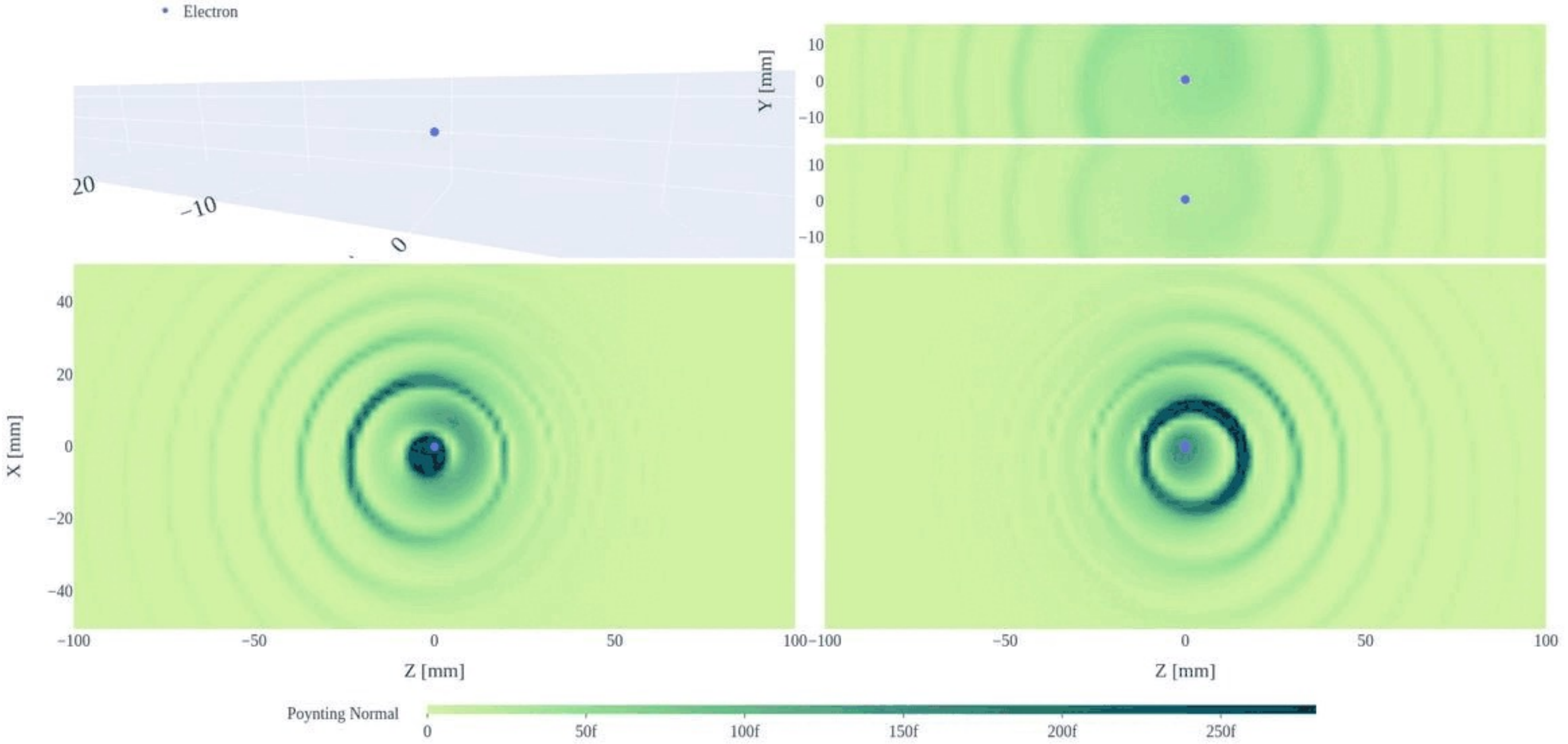
JOHN TEMPLETON FOUNDATION

Pitch 85 Long Trajectory

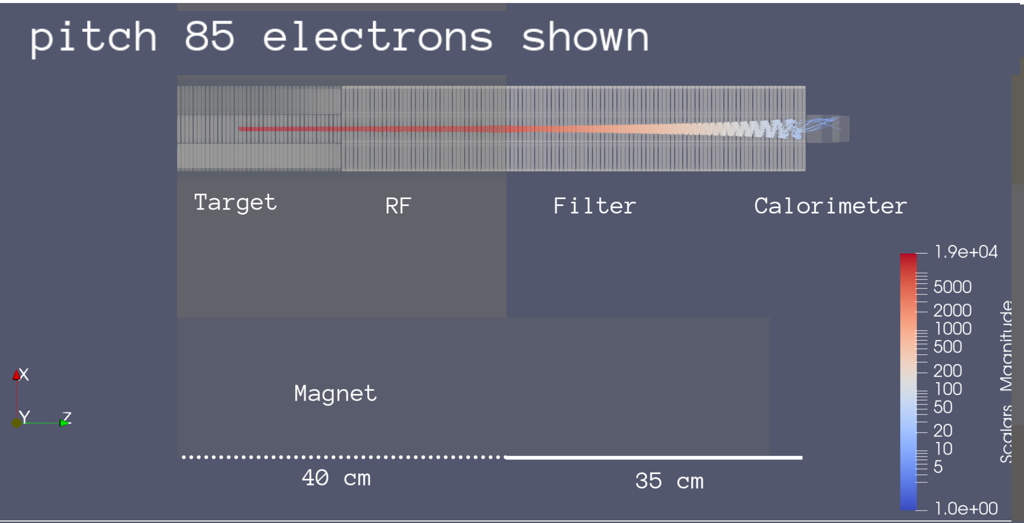


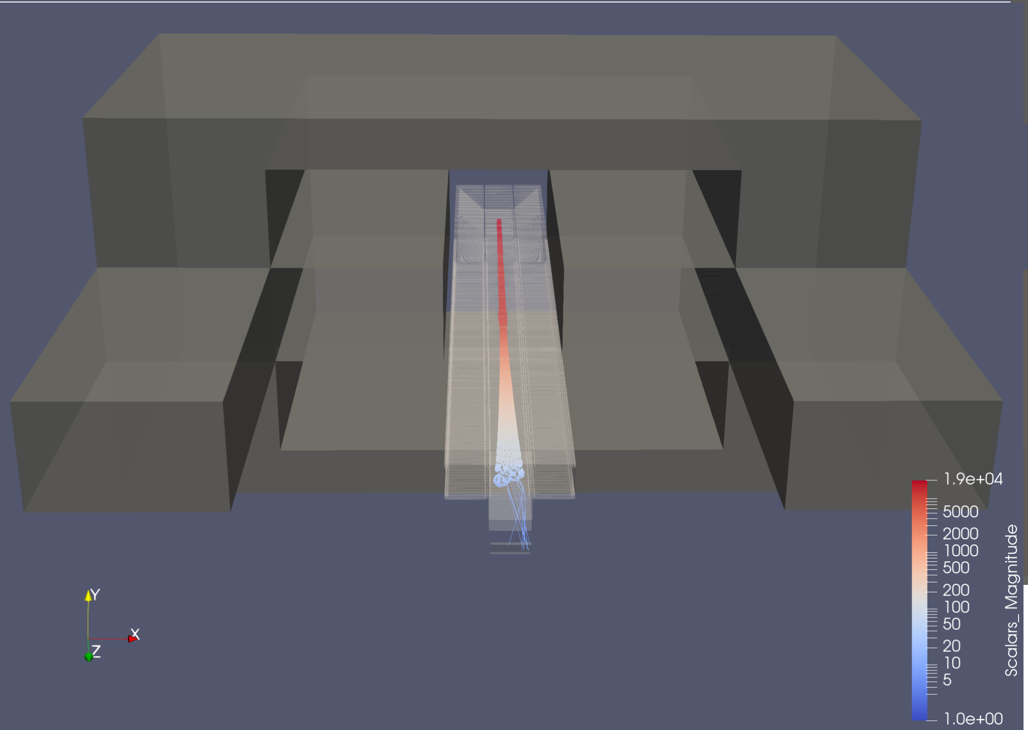


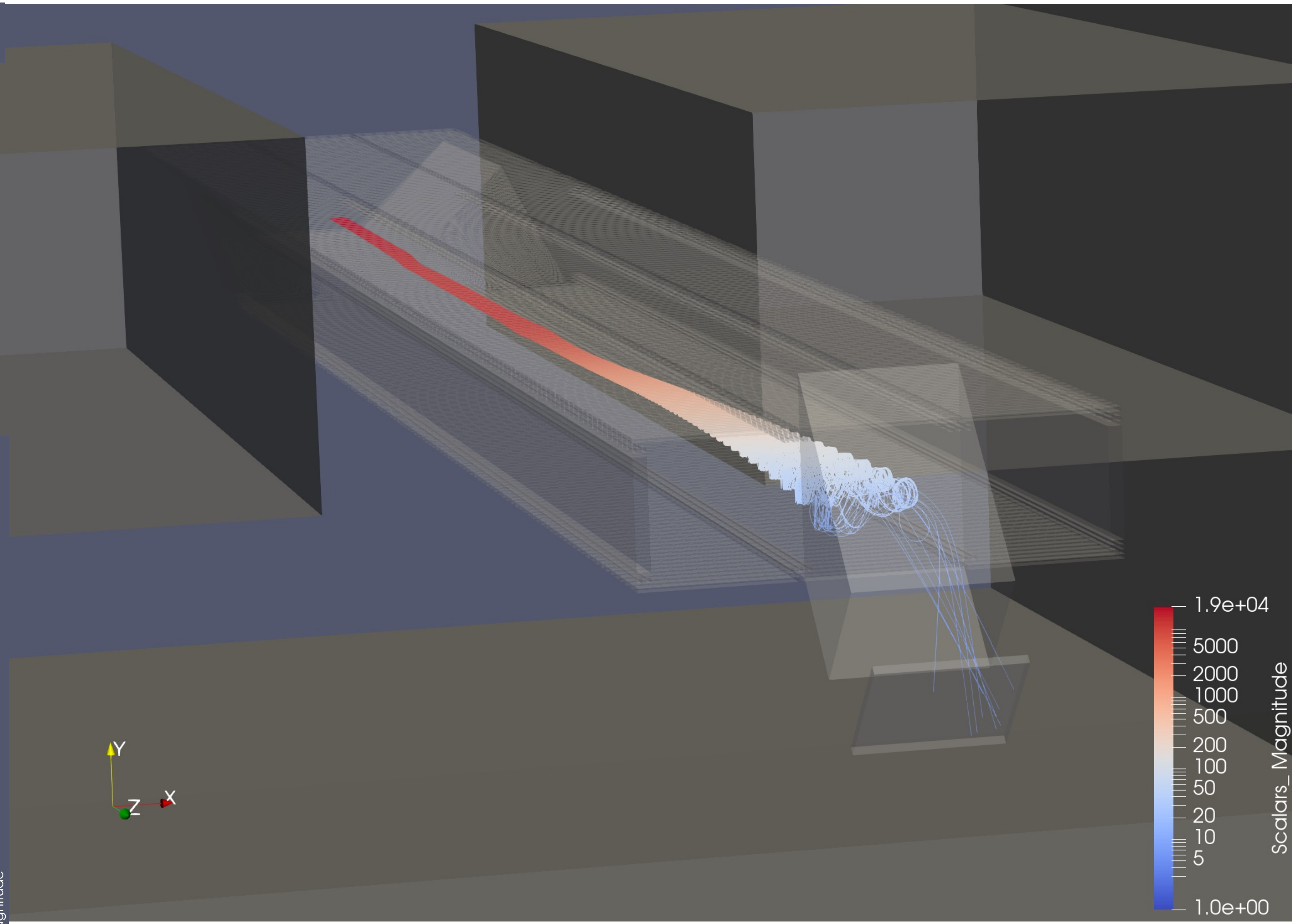
RF Calculation


Electron
Y [mm]
X [mm]
Z [mm]
Z [mm]
Poynting Normal
0
50f
100f
150f
200f
250f

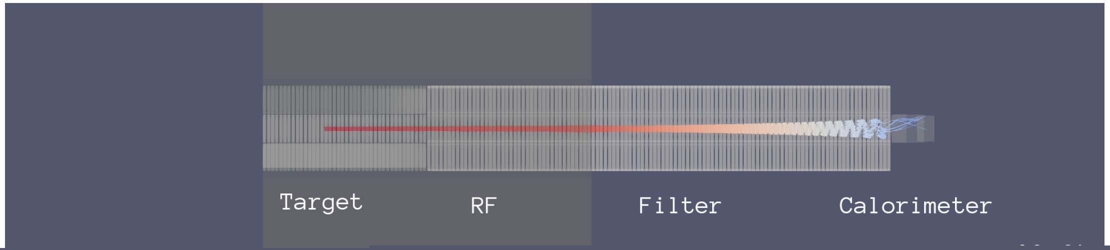
End-to-end Transport w/Kassiopeia

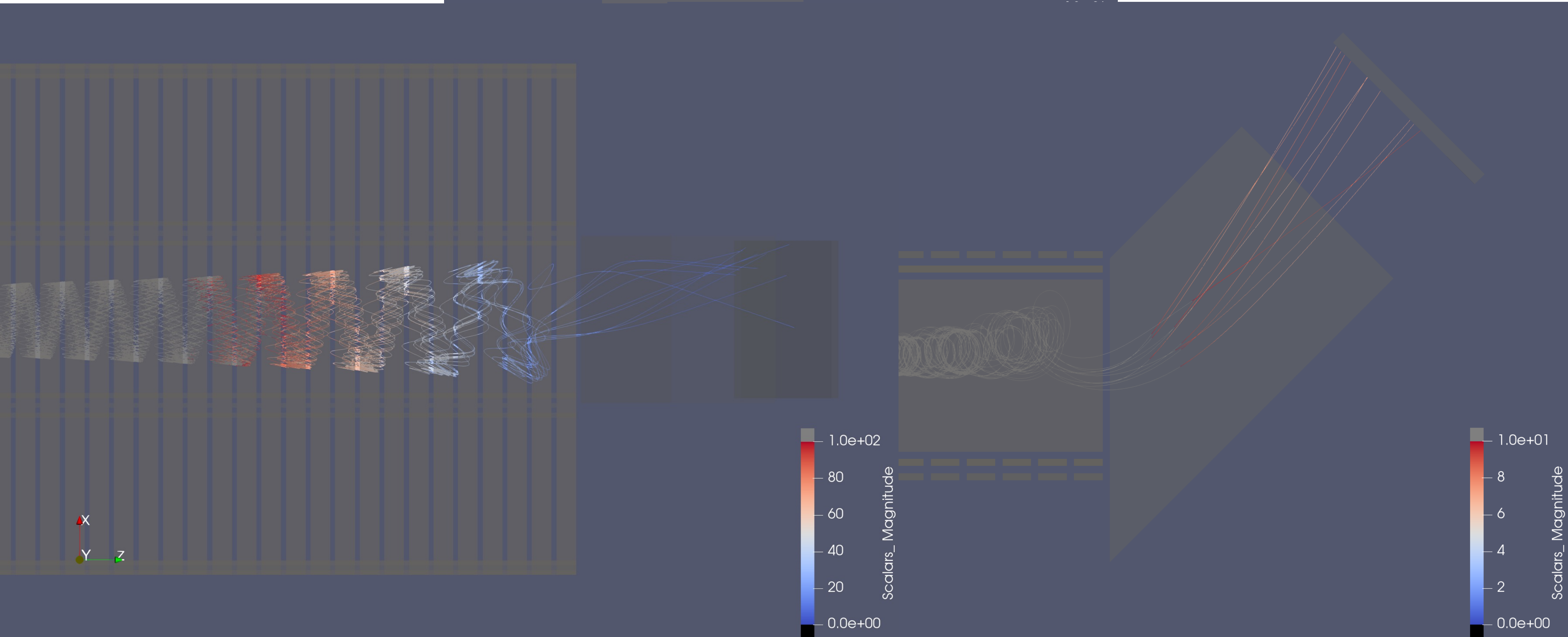






Zero-Field Calorimeter Transition

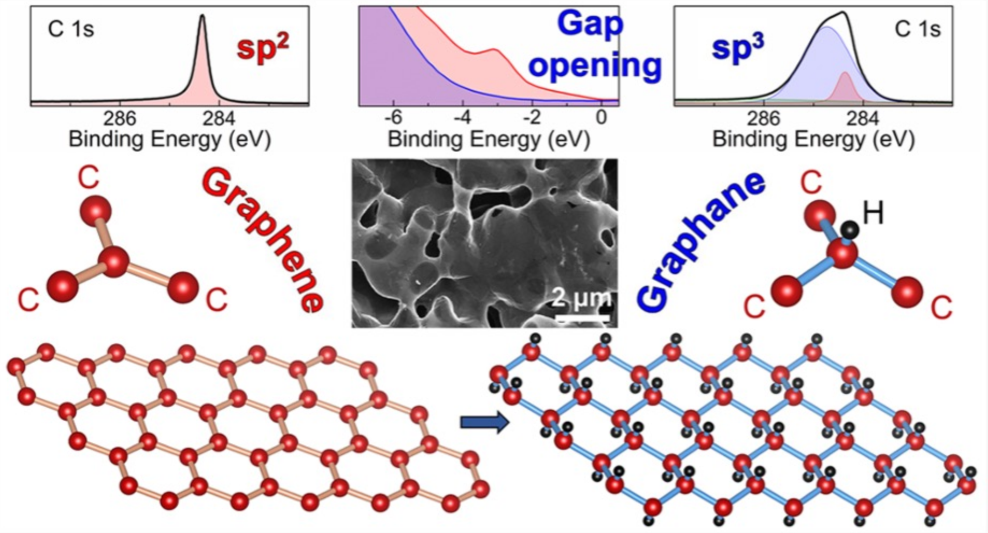




Gap Opening in Double-Sided Highly Hydrogenated Free-Standing Graphene

Maria Grazia Betti,* Ernesto Placidi, Chiara Izzo, Elena Blundo, Antonio Polimeni, Marco Sbroscia, José Avila, Pavel Dudin, Kailong Hu, Yoshikazu Ito, Deborah Prezzi,* Miki Bonacci, Elisa Molinari, and Carlo Mariani

ABSTRACT: Conversion of free-standing graphene into pure graphane—where each C atom is sp^3 bound to a hydrogen atom—has not been achieved so far, in spite of numerous experimental attempts. Here, we obtain an unprecedented level of hydrogenation (≈90% of sp^3 bonds) by exposing fully free-standing nanoporous samples—constituted by a single to a few veils of smoothly rippled graphene—to atomic hydrogen in ultrahigh vacuum. Such a controlled hydrogenation of high-quality and high-specific-area samples converts the original conductive graphene into a wide gap semiconductor, with the valence band maximum (VBM) ~ 3.5 eV below the Fermi level, as monitored by photoemission spectromicroscopy and confirmed by theoretical predictions. In fact, the calculated band structure unequivocally identifies the achievement of a stable, double-sided fully hydrogenated configuration, with gap opening and no trace of π states, in excellent agreement with the experimental results.



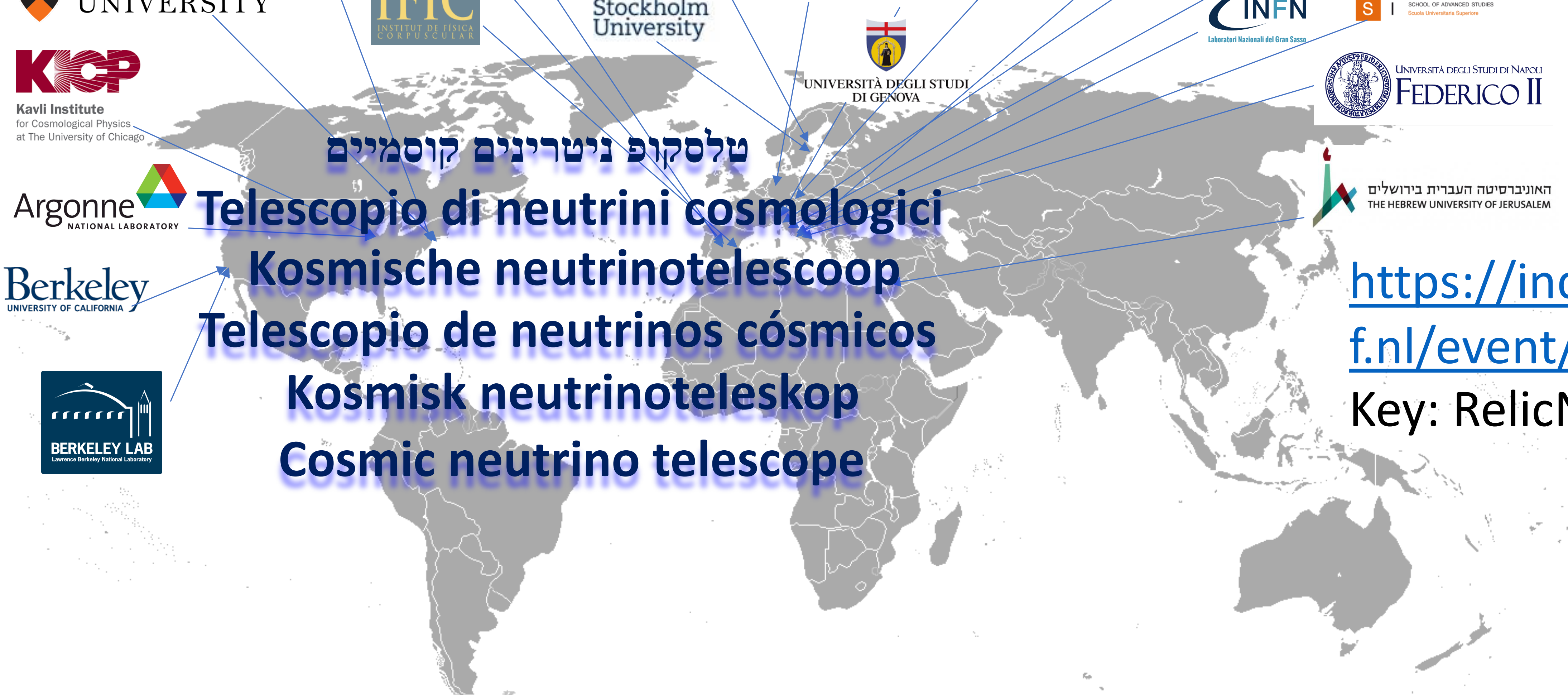
LNGS Full-Scale Prototype

JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

- Based on an initial test integration at Princeton:
  - Iron-return flux magnet
  - small planar 14-C target
  - RF antenna and tracking system
  - Cryostat
  - Filter electron HV
  - Tagging silicon detector
- Validate the construction design of the LNGS prototype and launch fabrication in Fall 2022
- Operate through 2024, then switch to superconducting coil

PTOLEMY Collaboration Meeting in Amsterdam

PPPL PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
KICP Kavli Institute for Cosmological Physics at The University of Chicago
Argonne NATIONAL LABORATORY
Berkeley UNIVERSITY OF CALIFORNIA
BERKELEY LAB Lawrence Berkeley National Laboratory
POLITÉCNICA
IFIC INSTITUT DE FISICA CORPUSCULAR
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
Stockholm University
UPPSALA UNIVERSITET
UNIVERSITY OF AMSTERDAM
Radboud University
Nikhef
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
UNIVERSITÀ DEGLI STUDI DI GENOVA
SAPIENZA UNIVERSITÀ DI ROMA
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
UNIVERSITÀ DI PISA
INFN Laboratori Nazionali del Gran Sasso
GSSI GRAN SASSO SCIENCE INSTITUTE SCHOOL OF ADVANCED STUDIES Scuola Universitaria Superiore
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM



טלסקופ ניטרינים קוסמיים

Telescopio di neutrini cosmologici

Kosmische neutrinotelescoop

Telescopio de neutrinos cósmicos

Kosmisk neutrinoteleskop

Cosmic neutrino telescope

https://indico.nikhef.nl/event/3724/

Key: RelicNeutrino!

Spare slides

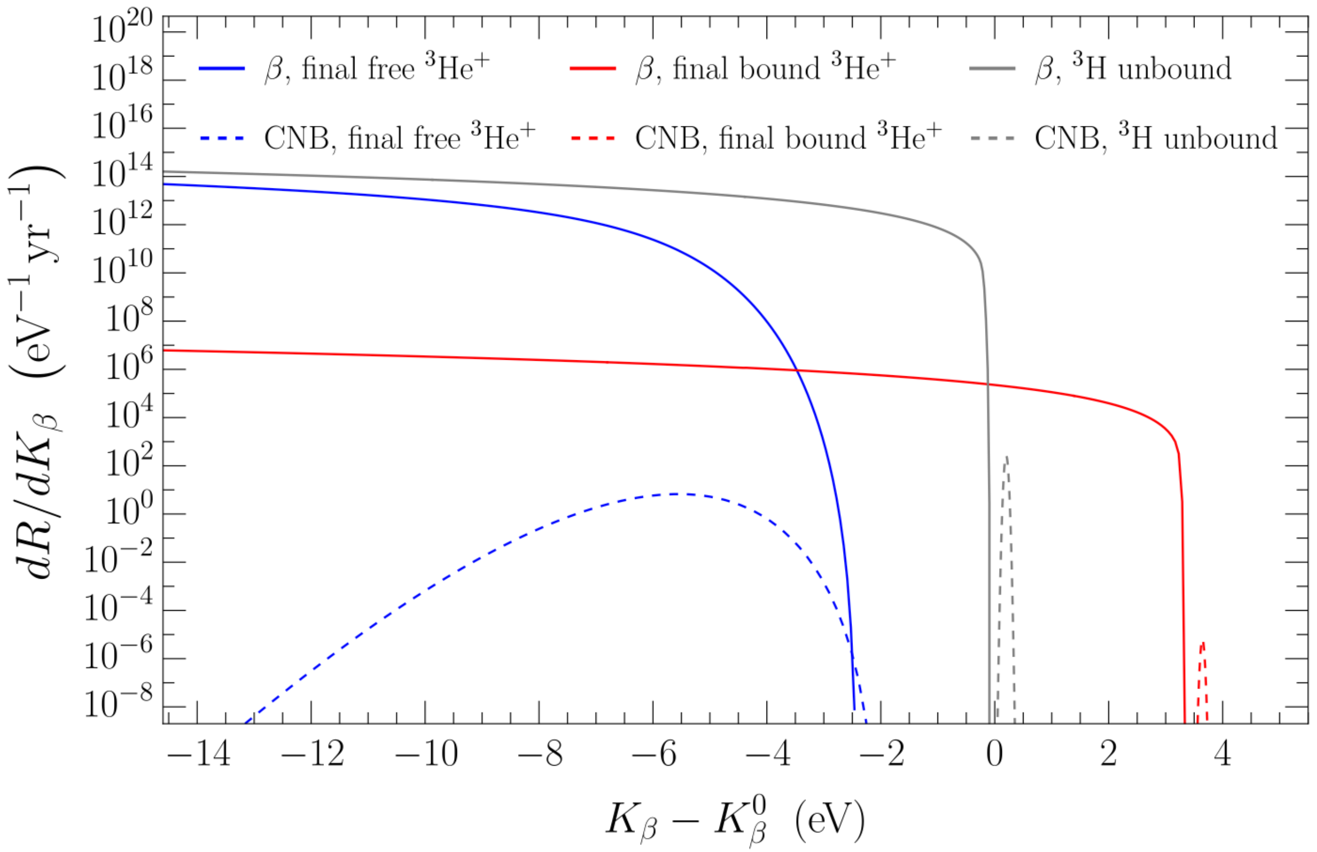
QUANTUM SPREAD – Tritium on flat graphene

spatially localized tritium → uncertainty on tritium's momentum * → spread in final electron energy

$^3He^+$ is mostly freed from the graphene → the cosmic neutrino peak disappears under the decay spectrum

When the $^3He^+$ remains bound in the ground state the peak is separated → it is however exponentially unlikely

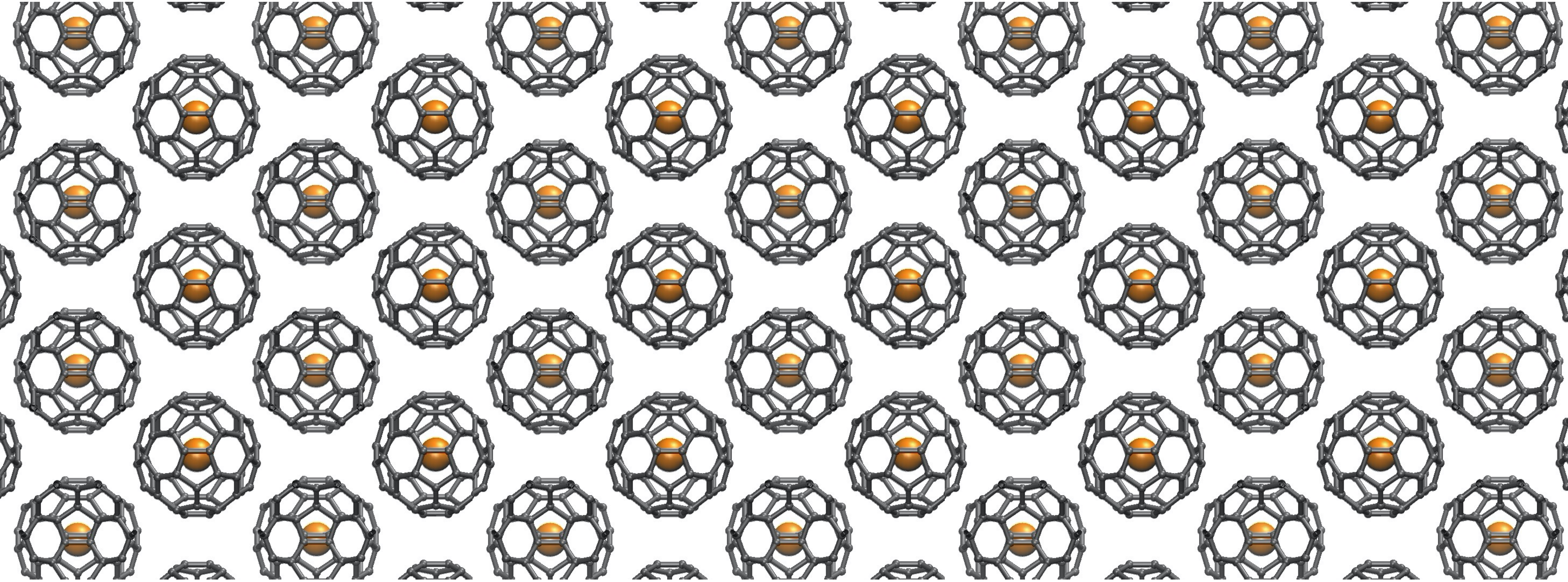
PTOLEMY
arXiv: 2203.11228



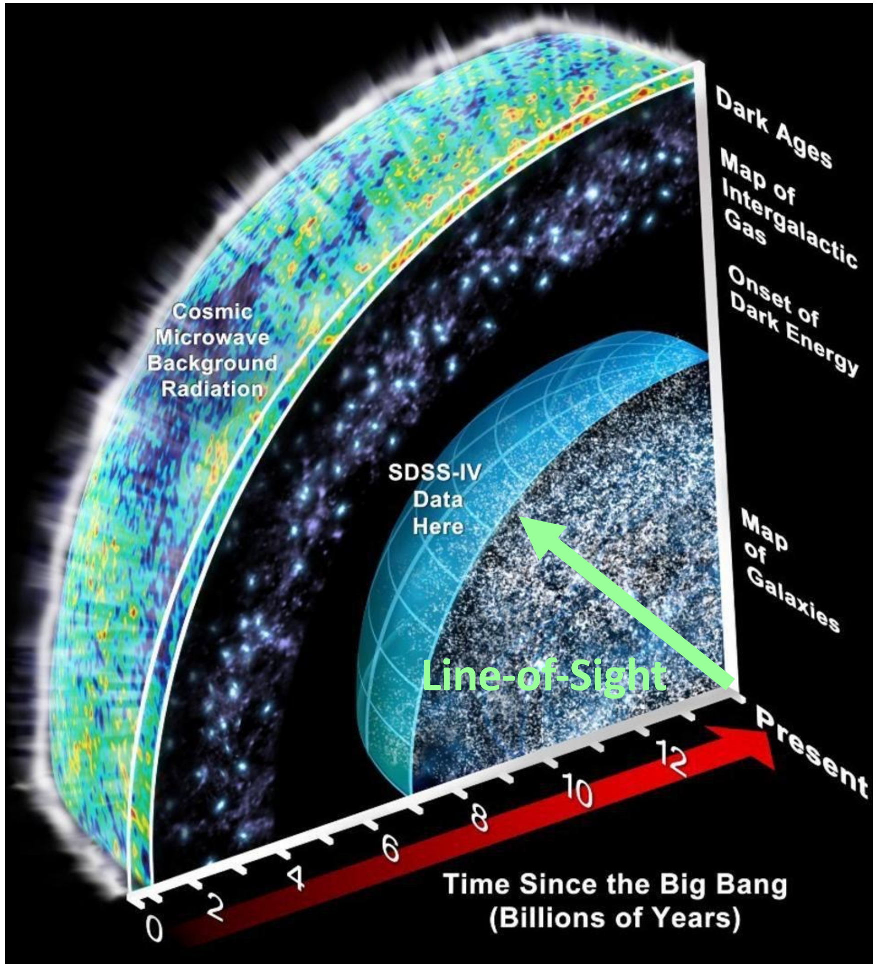
*Cheipesh, Cheianov & Boyarsky *Phys. Rev. D* **104**, 116004

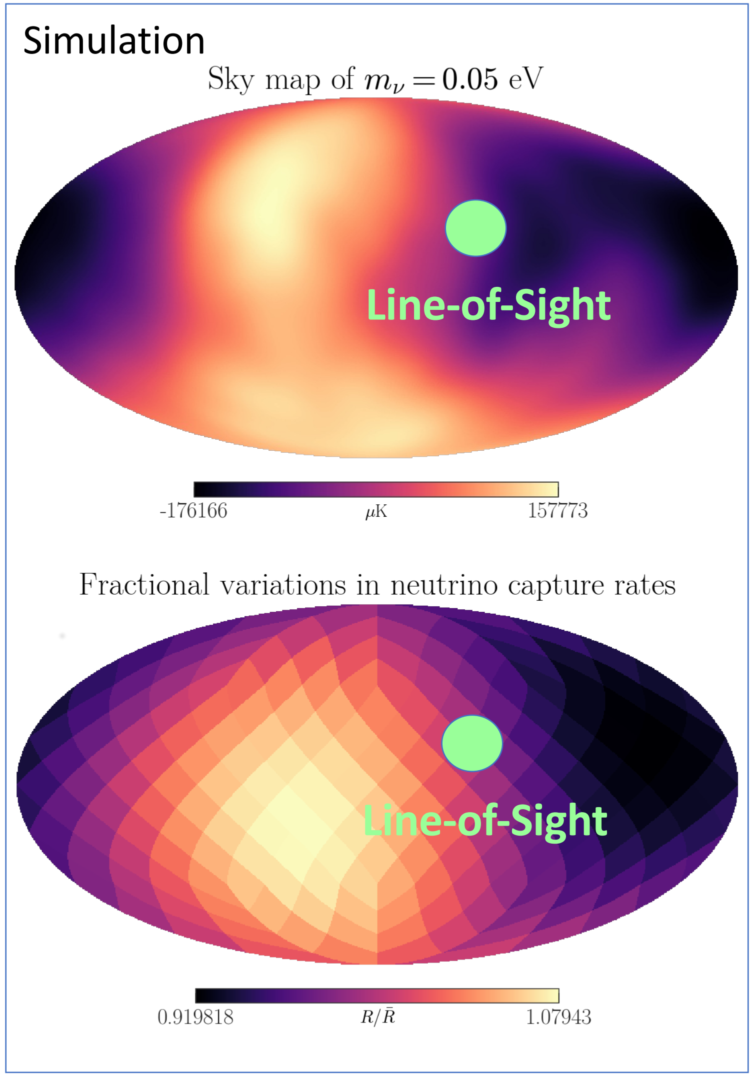
De-localized Atomic T Geometries

~2Å flat potential – not chemically active



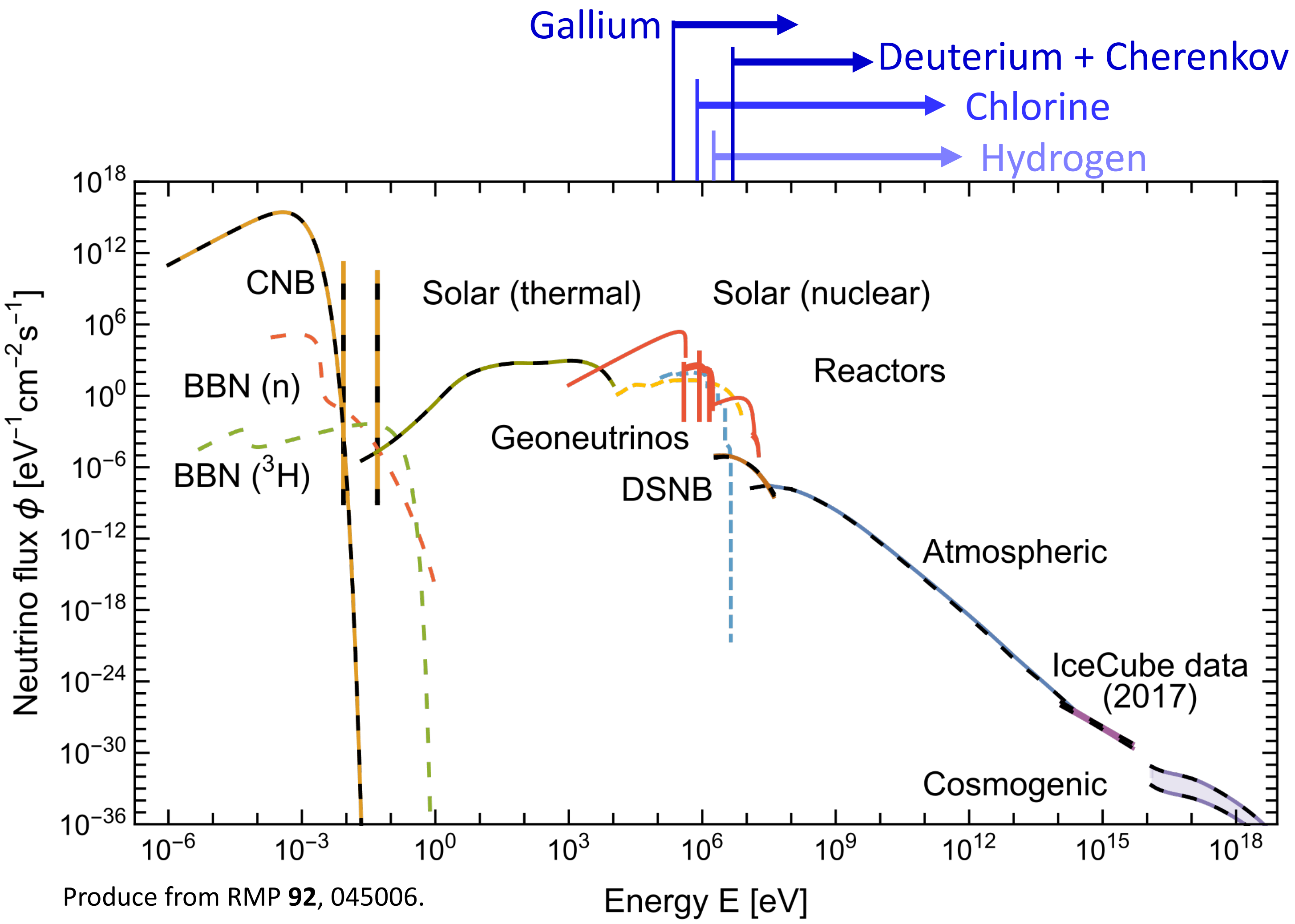
Relic Neutrino Sky Map





Tully, Zhang, “Multi-Messenger Astrophysics with the Cosmic Neutrino Background”, JCAP 06 (2021) 053

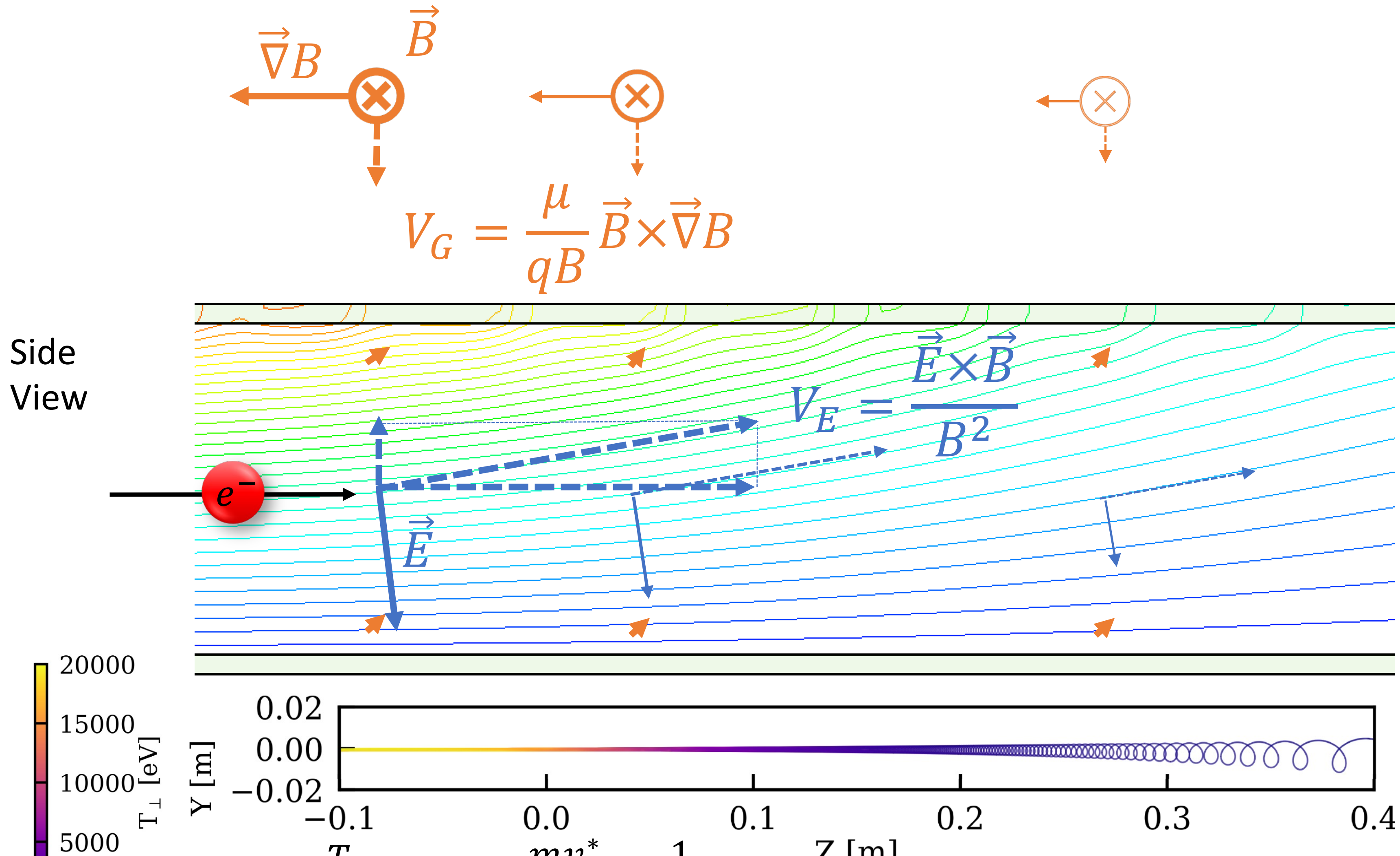
Cosmic Neutrino Background



Produce from RMP **92**, 045006.

- The CNB is shown for a minimal mass spectrum here for 0, 8.6, and 50 meV, producing a blackbody spectrum plus two monochromatic lines for nonrelativistic neutrinos with energies corresponding to their masses.
- Detection requires a reaction with no threshold.

PTOLEMY Electromagnetic Filter



$$\mu = \frac{T_\perp}{B} \qquad \rho_C = \frac{mv_\perp^*}{qB} \propto \frac{1}{\sqrt{B}}$$

Control electrons by:

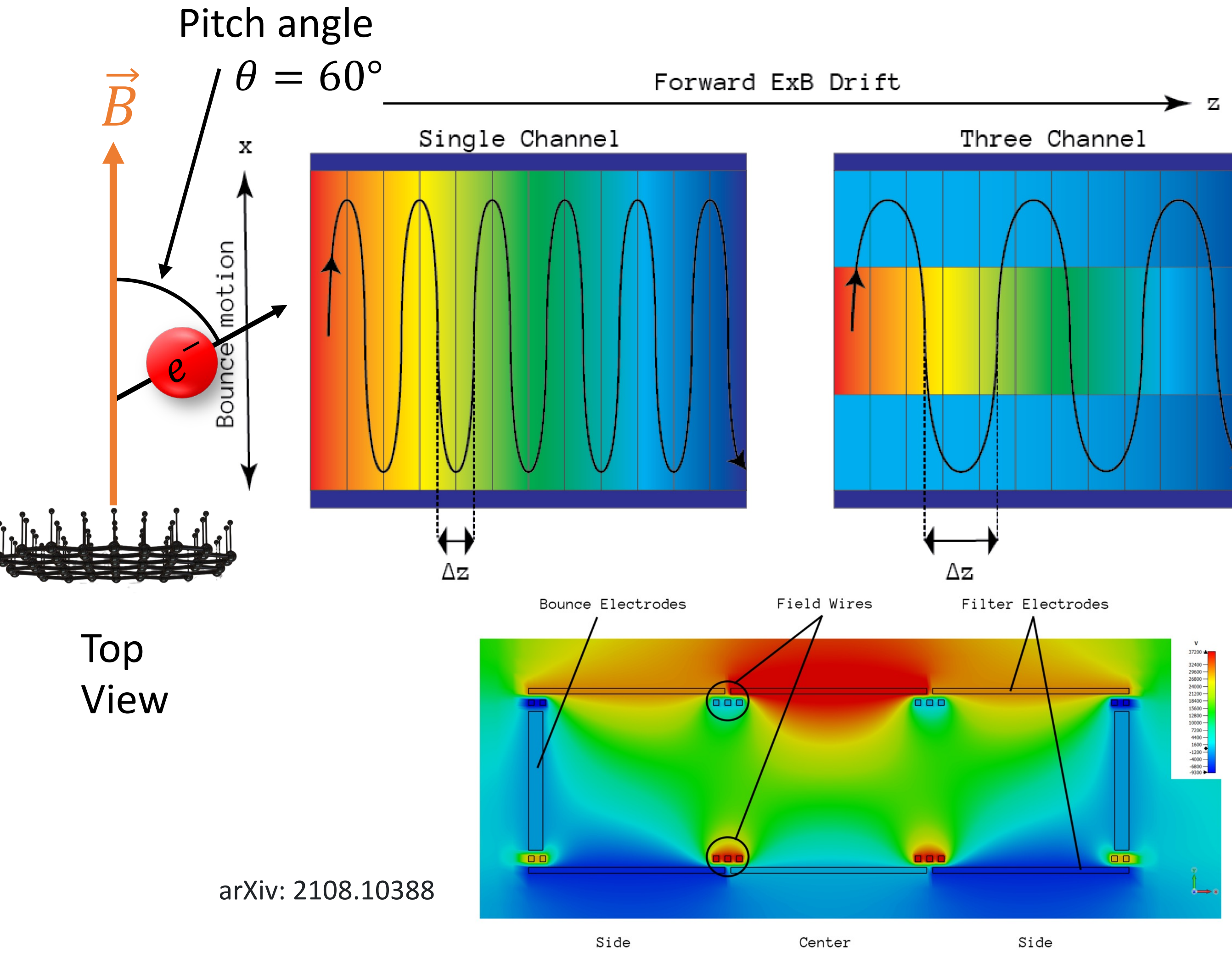
- B field
- Bounce potential

Filter (push them up the potential hill) & Guide them to the colorimeter by:

- $E\times B$ drift
- $B\times\nabla B$ drift
- Curvature

$E\times B$ term drifts along the equal potential lines. Therefore, combine it with $B\times\nabla B$ term.

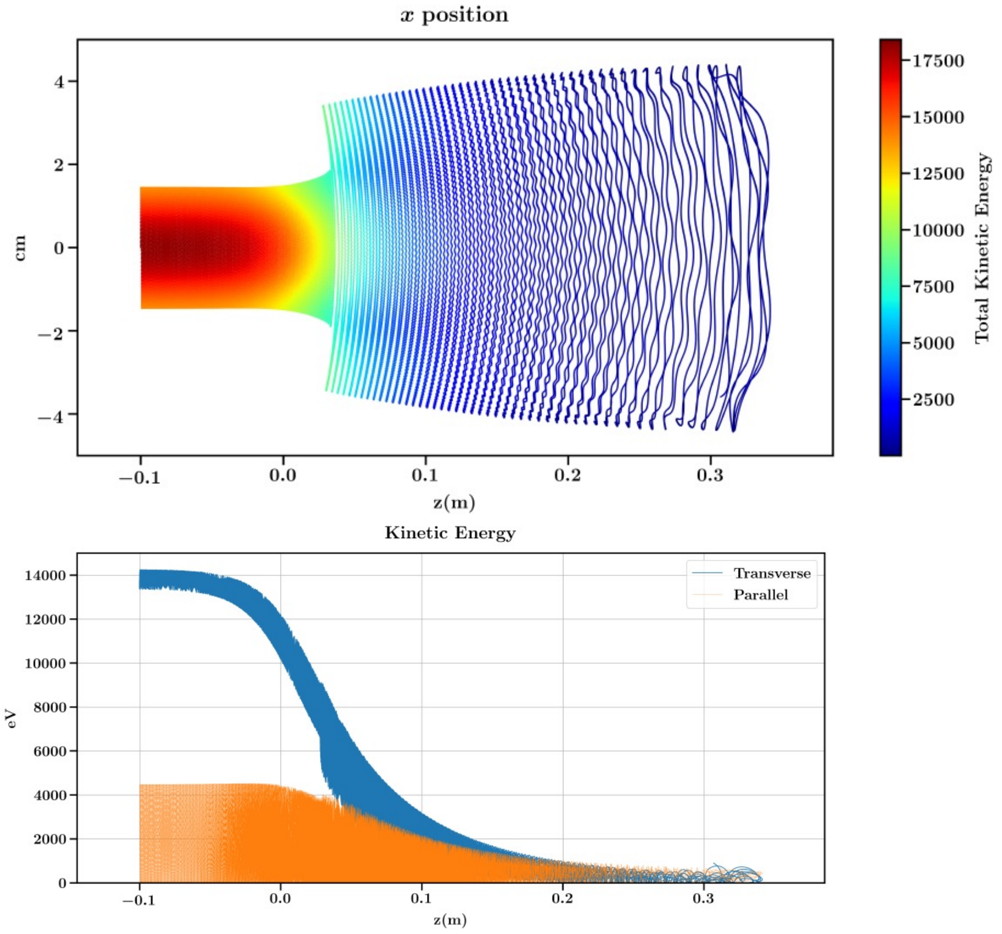
PTOLEMY EM Filter with 3 Channels



arXiv: 2108.10388

- To increase the acceptance for low pitch angle ones, we split the bounce direction into 3 channels (central, side).
- Electrons linger in the side well longer in a 3-channel design, s.t. the parallel kinetic energy drains faster than the transverse one to avert a runaway drift.
- By raising the side well potentials, the electrons enter the side well with lower parallel kinetic energy than the single channel design.

PTOLEMY 3-Channel EM Filter

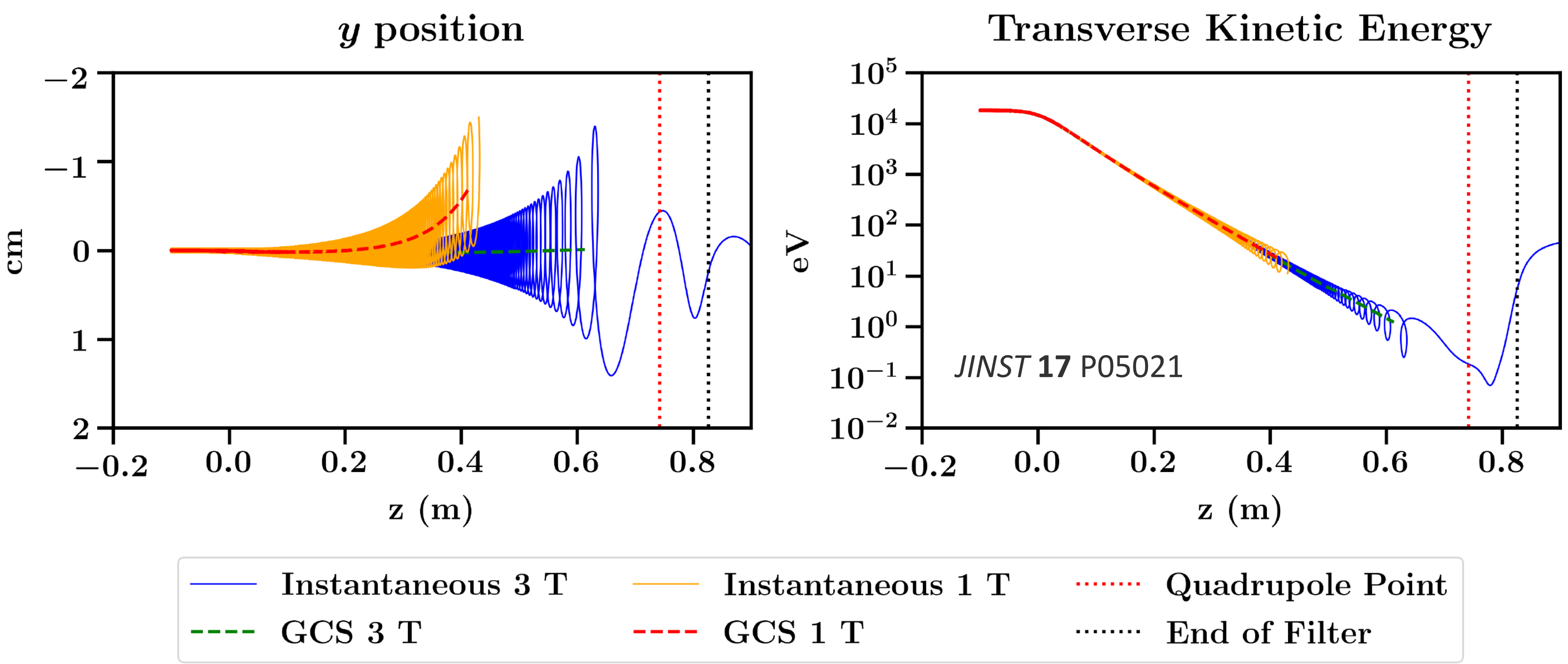


arXiv: 2108.10388 submitted to RSI

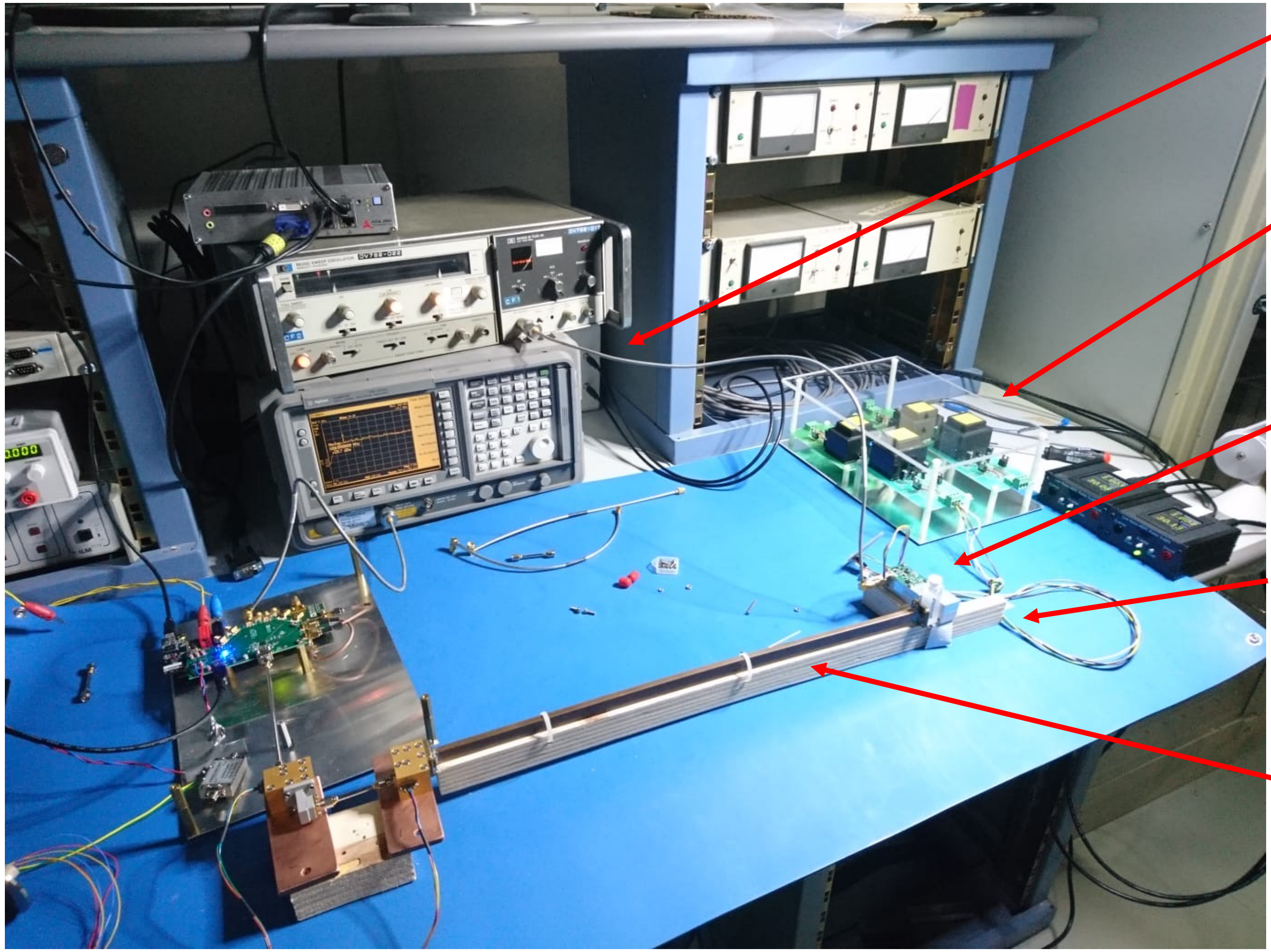
- An example of the trajectory (top view) of an electron with $\theta = 60°$ in a 3-channel filter.
- Both its parallel and transverse kinetic energies drains as it drifts along +z direction where the B field decays.

Filter Performance

Improves as B^2 for a fixed filter dimension
18.6 keV @ 1T → ~10eV (in 0.4m)
18.6 keV @ 3T → ~1eV (in 0.6m)



LNGS RF Setup



Signal injection: ~13 GHz

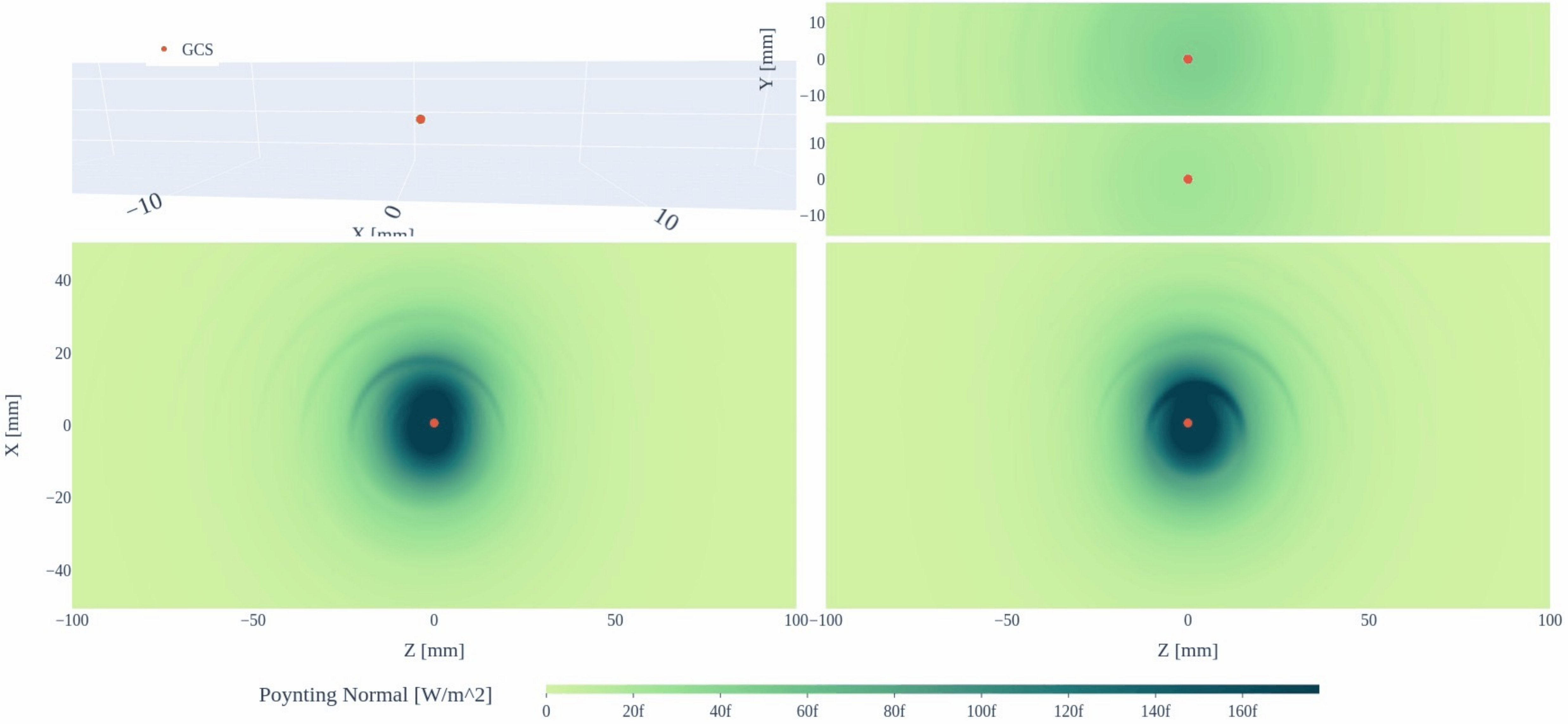
4 Low voltage channels

Frequency multiplier

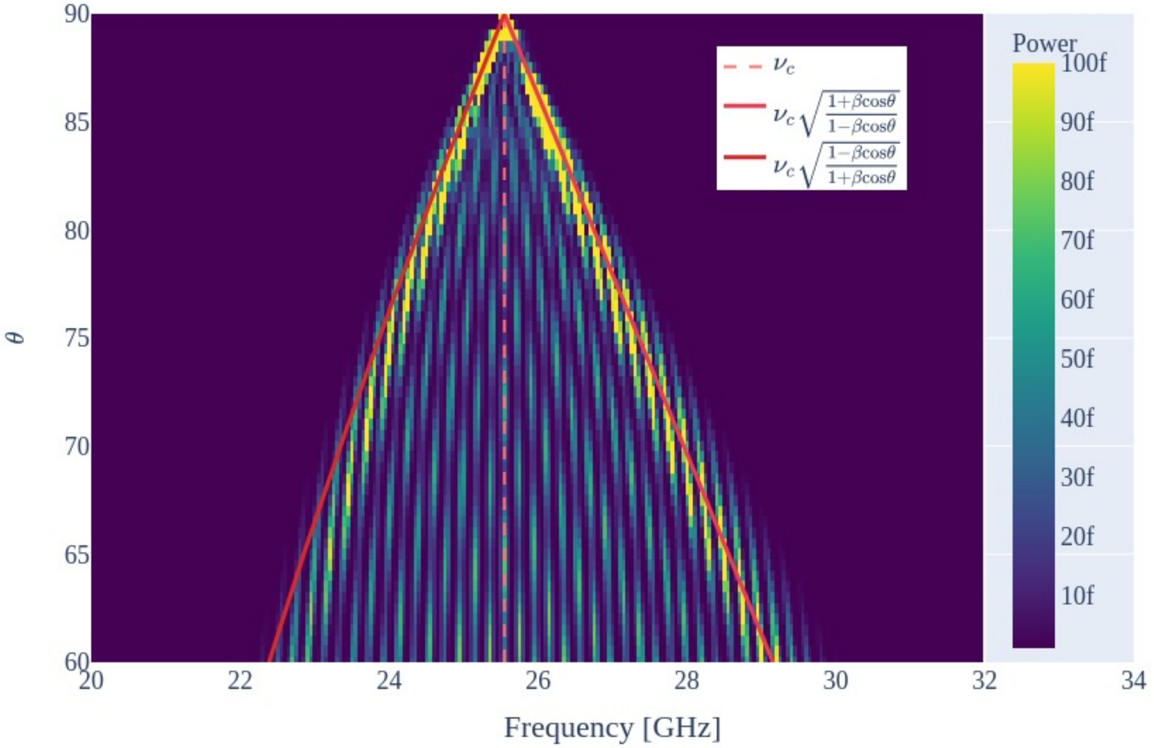
Calibrated 1 cm
water absorber

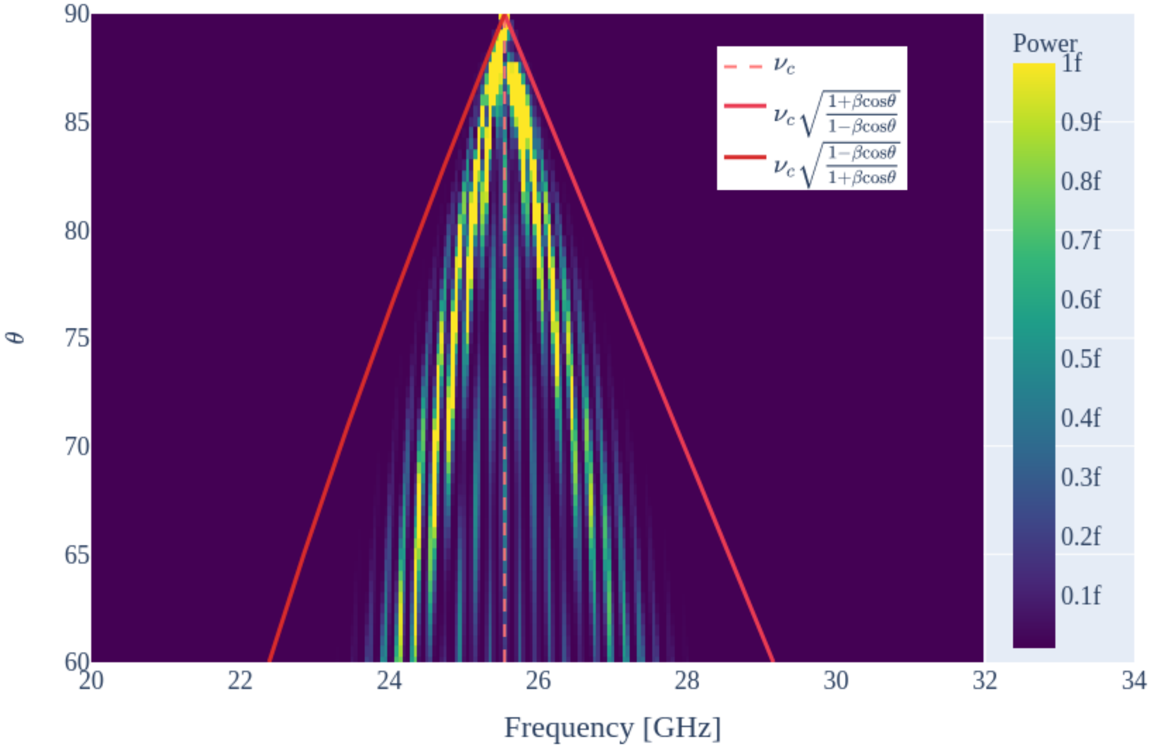
WR42 Waveguide
from Princeton

Alfredo Cocco, George Korga, Marcello Messina


GCS
−10
0
X [mm]
10
Y [mm]
10
0
−10
10
0
−10
X [mm]
40
20
0
−20
−40
−100
−50
0
50
100
−100
−50
0
50
100
Z [mm]
Z [mm]
Poynting Normal [W/m^2]
0
20f
40f
60f
80f
100f
120f
140f
160f

Doppler Shifting vs. Antenna Position

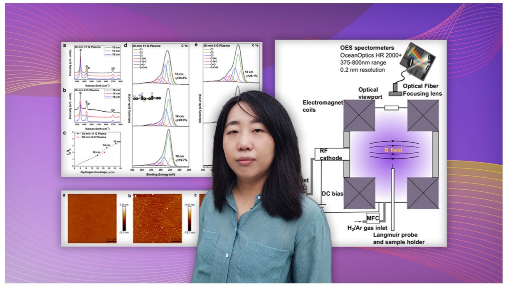




Antenna Angular Gain not yet applied – still evaluating options

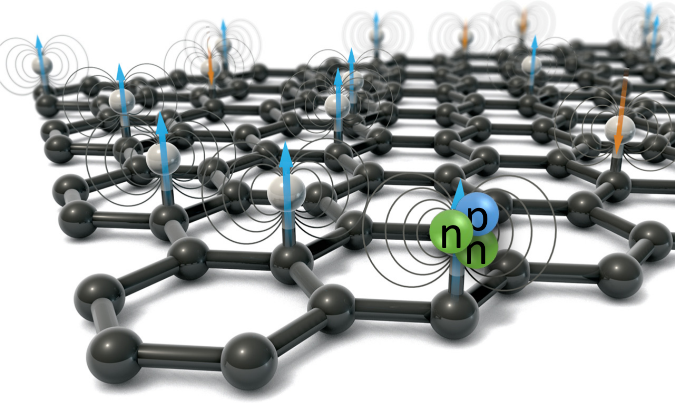
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Plasma to the rescue: Scientists develop a path-setting method to enable vast applications for a promising nanomaterial



Physicist Fang Zhao with figure from her paper. (Photo courtesy of Fang Zhao.)

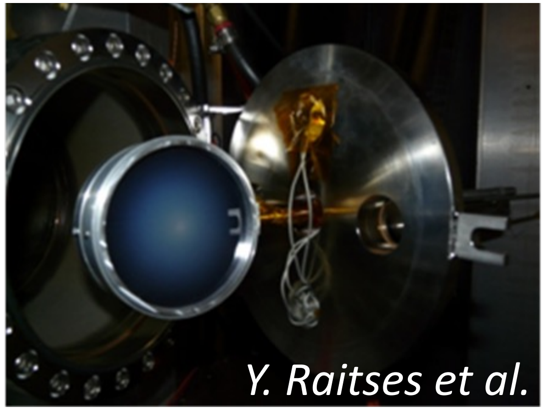
John Greenwald

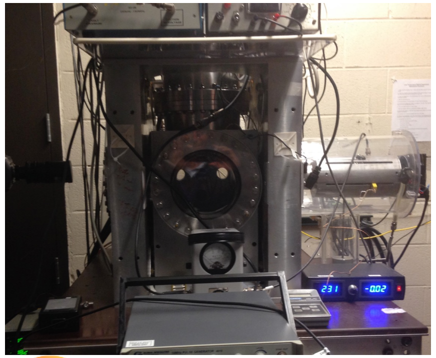


Courtesy: C. BICKEL/*SCIENCE*

JOHN TEMPLETON FOUNDATION

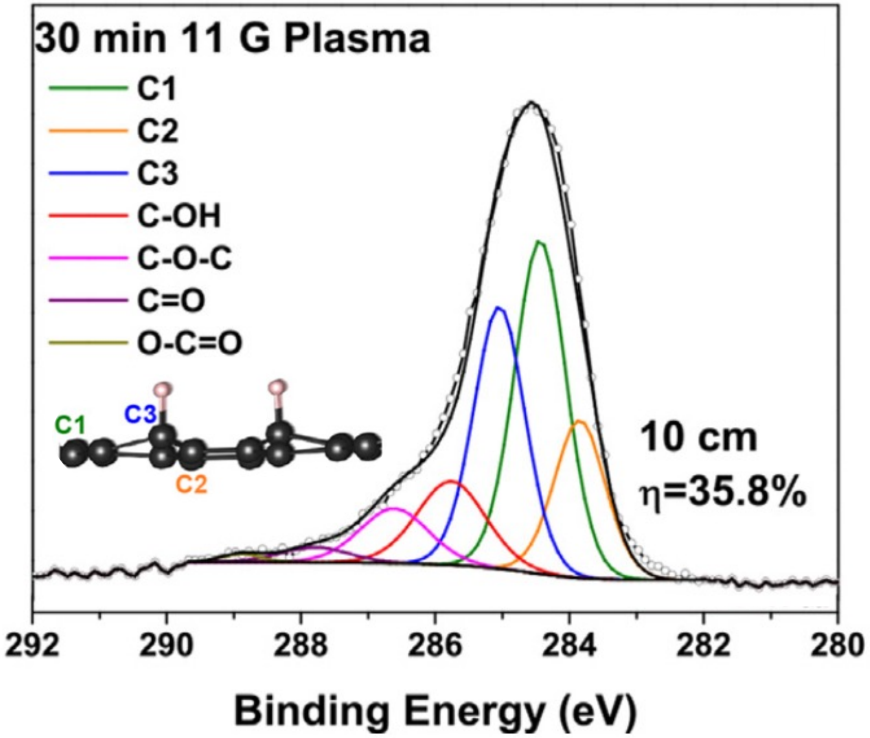
Tritium Source





PPPL PRINCETON PLASMA PHYSICS LABORATORY

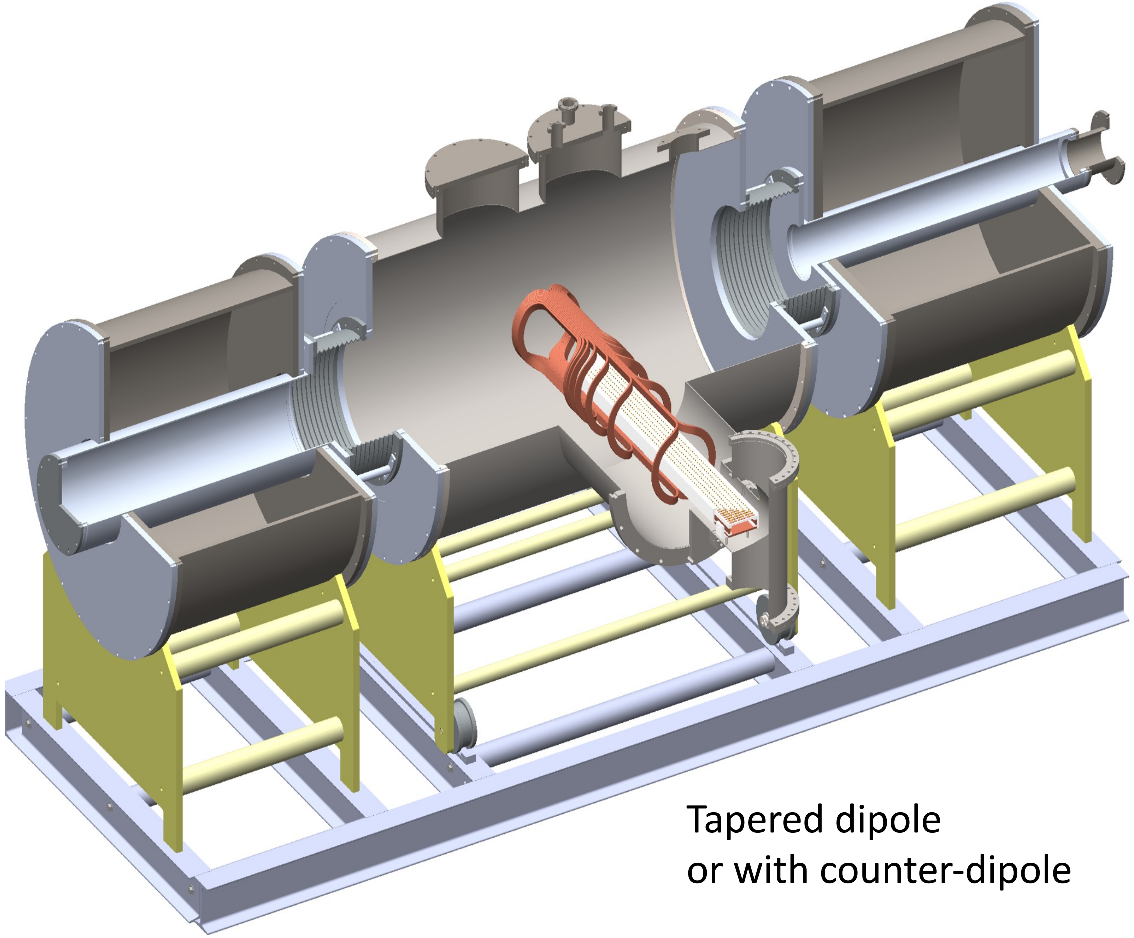
- Atomic tritium Source
  - No ro-vibrational modes in final state like for diatomic molecular source (4.7 eV covalent bond)
- Tritium load on graphene
  - 0.7-1.0eV covalent bond
  - High coverage
  - Stable at room temperature
  - Polarized T -> directionality *
- Other ideas
  - Au(111)
  - Superfluid Helium

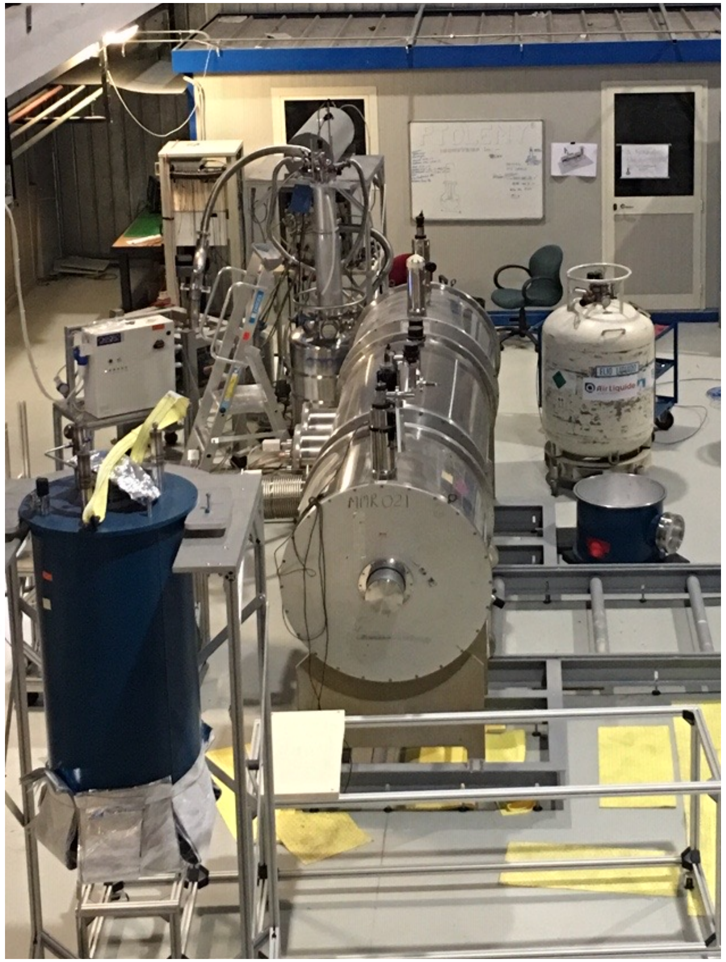


Carbon 177 (2021) 244-251

*Lisanti, Safdi, and Tully, PRD **90**, 073006 (2014)

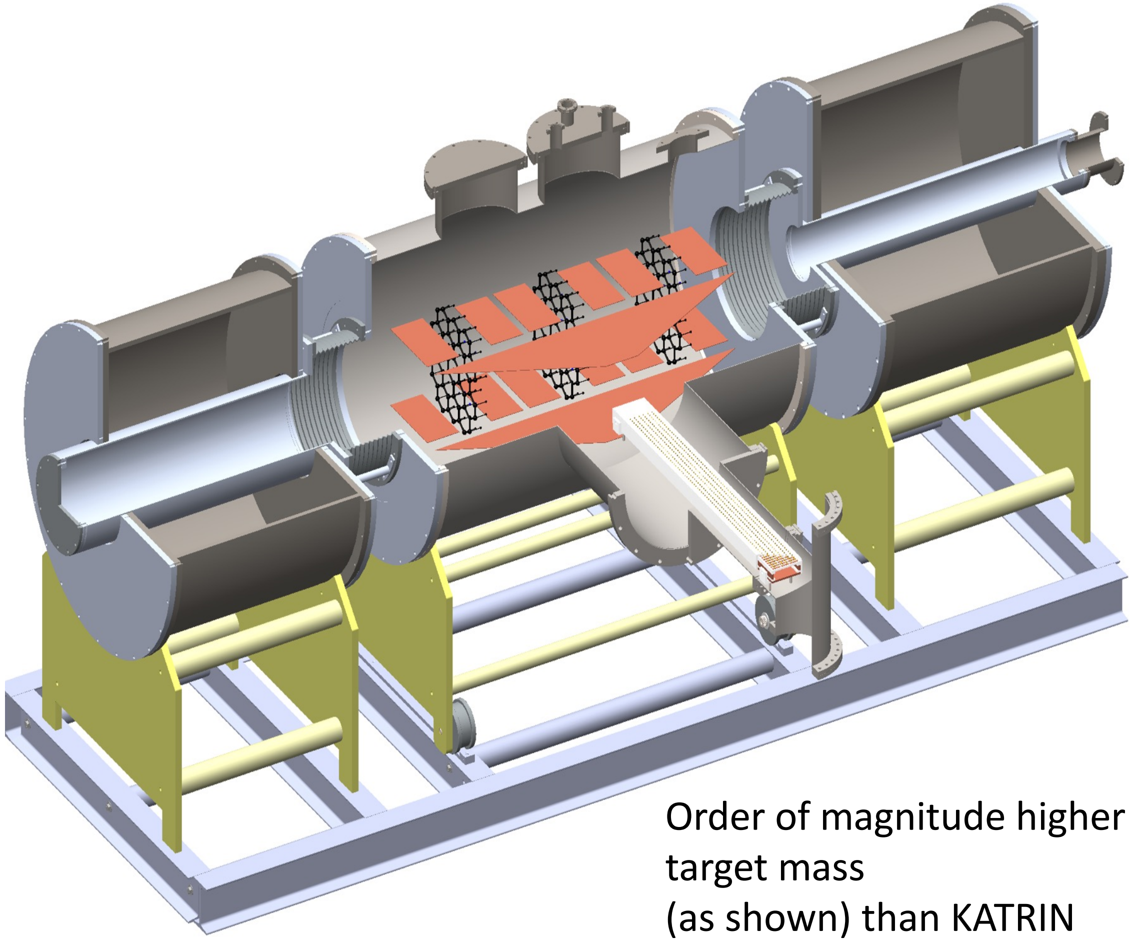
Superconducting Coil Design



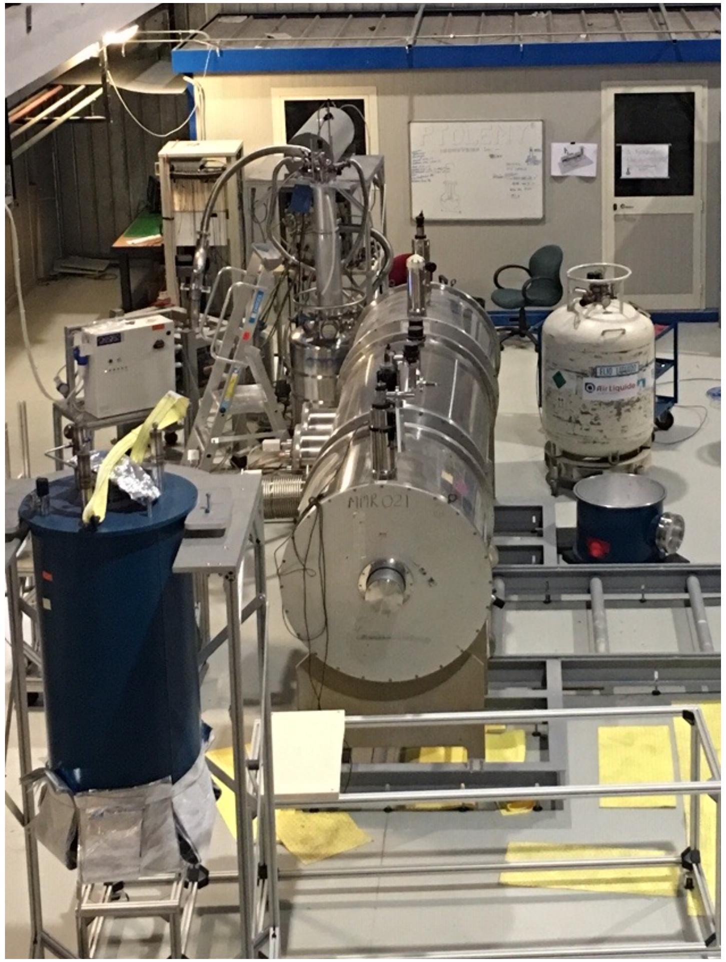


Integrate into existing dual-SC magnet setup @ LNGS

Large Area Target Design

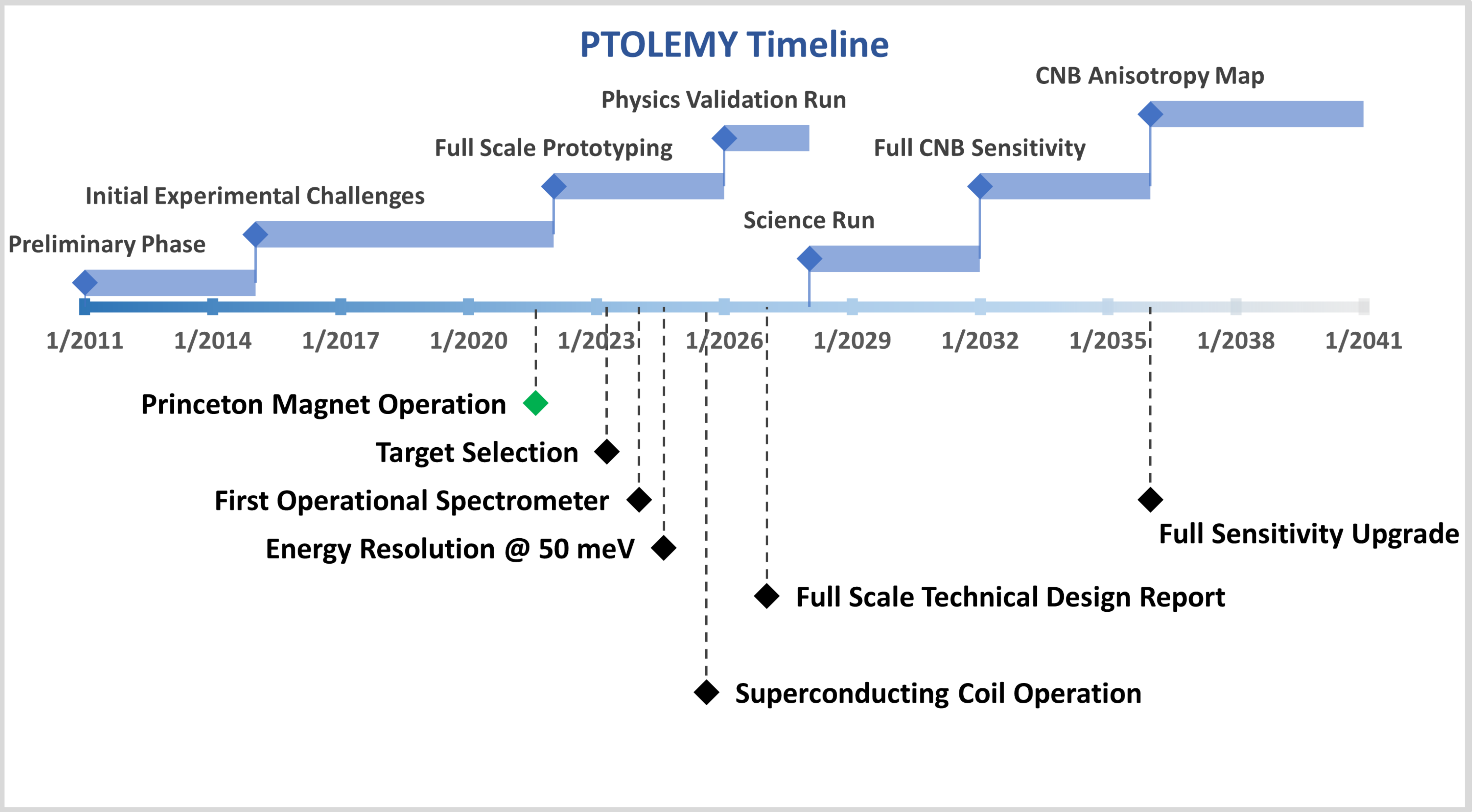


Order of magnitude higher
target mass
(as shown) than KATRIN



Target Area and Quantum Properties are final frontiers for PTOLEMY

Yevheniia Cheipesh, Vadim Cheianov, Alexey Boyarsky, https://arxiv.org/abs/2101.10069
"Navigating the pitfalls of relic neutrino detection"


PTOLEMY Timeline
CNB Anisotropy Map
Physics Validation Run
Full Scale Prototyping
Full CNB Sensitivity
Initial Experimental Challenges
Science Run
Preliminary Phase
1/2011
1/2014
1/2017
1/2020
1/2023
1/2026
1/2029
1/2032
1/2035
1/2038
1/2041
Princeton Magnet Operation
Target Selection
First Operational Spectrometer
Energy Resolution @ 50 meV
Full Sensitivity Upgrade
Full Scale Technical Design Report
Superconducting Coil Operation

CNB detection principles have evolved into concrete designs

Prototype construction has yielded good results with several publications.

We hope to enter an exciting new phase with PTOLEMY this year with a rich experimental program.

Please join us the PTOLEMY meeting in Amsterdam.

https://indico.nikhef.nl/event/3724/

Key: RelicNeutrino!